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Pathfinder

Program Overview

Fall 1988



*Research and Technology
to Enable Future
Space Missions*

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FIGURE

National Aeronautics and
Space Administration

Office of Aeronautics and
Space Technology
Washington, D.C. 20456

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Foreword

Pathfinder is a technology initiative that will allow the National Aeronautics and Space Administration (NASA) to develop critical capabilities to enable future missions of solar system exploration. This programmatic scope includes both human exploration missions as well as robotic science missions and robotic precursors to later human expeditions.

Pathfinder is not a mission, nor is the program directed toward any specific mission concept. Through **Pathfinder**, the NASA Office of Aeronautics and Space Technology (OAST) will develop critical information and capabilities in the areas of surface exploration, in-space operations, humans in space technologies, and space transfer systems. **Pathfinder** will - as the Apollo program did during the 1960s - push American technology forward, while making future successes in space possible.

This document provides a detailed overview of **Pathfinder**, including its goals and objectives, technical content, and the organization and management of the Program.

Pathfinder

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Pathfinder

Overview

Chapter 1 Overview

Pathfinder is a new technology initiative that will allow the National Aeronautics and Space Administration (NASA) to develop critical capabilities to enable future missions of solar system exploration. This programmatic scope includes both human exploration missions as well as robotic science missions and robotic precursors to human expeditions.

This document provides an overview of the Pathfinder program, including not only its goals and objectives, but also the technical and programmatic details of Pathfinder, and the technology thrusts and several element programs that make up the program.

Section 1.1 Background

The past 25 years of the civil space program have presented the United States with a broad ensemble of spectacularly successful planetary exploration missions. These have spanned the spectrum from the earliest automated spacecraft flybys of the Moon and Mars through the achievement of the Apollo program's piloted missions to the Moon. Today, NASA continues that tradition of planetary exploration through missions such as Galileo to Jupiter, Magellan to

Venus, and the Mars Observer. Beyond these near term probes, the future holds still more exciting opportunities.

Since before the beginning of the U.S. civil space program, there has been considerable speculation about possible human and robotic exploration of the solar system. Over the years, those speculations have been crystallized by numerous formal studies by NASA and others, of ambitious future missions. Recently, the National Commission on Space (NCOS) examined the prospects for future U.S. space activities and discovered an exciting vista of possibilities.

NASA is working to reexamine in detail the options and possibilities for future space



science, space operations, and the robotic and human exploration of the solar system. Studying options for future human exploration is the responsibility of the NASA Office of Exploration (OEXP). The NASA Office of Space Science and Applications

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(OSSA) is responsible for robotic exploration and is conducting various missions studies, including potential precursors to human missions such as Mars rover and sample return mission concepts. To provide operational support to these missions, the NASA Offices of Space Flight (OSF) and Space Station (OSS) are studying advanced in-space operational capabilities that could be implemented in the late 1990s or the early part of the next century to support these ambitious solar system exploration missions.¹

The common thread that links these future possibilities is the need for substantial, across-the-board advances in space technology, coupled with the need for early information on the capabilities that technology will be able to provide. Within NASA, research and development of advanced space technology is carried out by the Office of Aeronautics and Space Technology (OAST). Through the Research and Technology (R&T) Base, OAST provides the technological foundations for the U.S. civil space program. That foundation is focused through two programs: CSTI² (the Civil Space Technology Initiative), and *Pathfinder*.

Section 1.2 Goals and Objectives

There are three major goals which OAST will achieve through *Pathfinder*. First,

Pathfinder will develop critical technology opportunities for a range of future

1. Additional information on NASA's current efforts in Solar System Exploration mission studies is provided in Chapter 6.
2. For information on CSTI, or any other aspect of OAST's programs, please contact the OAST Space Directorate.

space missions - focusing on exploration of the Solar System.

Second,

Pathfinder will support national decisions regarding future missions in the early 1990s timeframe.

And lastly,

Pathfinder will help to insure U.S. leadership in civil space technology development.

To meet those goals, the *Pathfinder* Program must achieve the following objectives: *Pathfinder* must

Produce initial critical research results and validate key capabilities by the early 1990s (initial target: the end of 1992);

Achieve necessary levels of readiness and transfer technologies to mission users beginning in the mid 1990s;

Define and achieve the right balance between more basic research and focused demonstrations;

Coordinate Pathfinder research and technology with other NASA Offices and support ongoing NASA mission studies; and,

Build a lasting partnership among NASA, U.S. industry, and universities in the implementation of Pathfinder.

OAST has formulated the *Pathfinder* Program to meet these goals and objectives. The remainder of this chapter provides a description of the organization and management of *Pathfinder*. Details regarding the technical content of the program are provided in Chapters 2 through 5.

Section 1.3

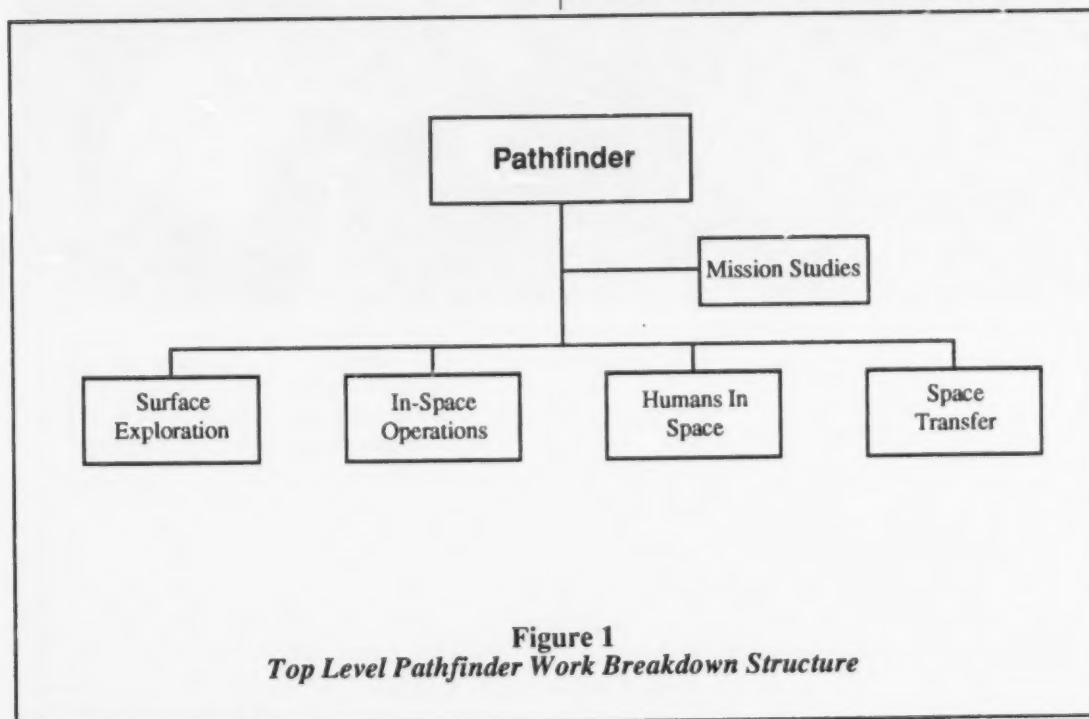
Management & Organization

Pathfinder is a focused technology program, consisting of a suite of research and development efforts that are divided into four major program areas. These are: (1) surface exploration, (2) in-space operations, (3) humans in space, and (4) space transfer. In addition, Pathfinder supports studies of future human and robotic solar system exploration missions. Figure 1 provides the Pathfinder work breakdown structure (WBS).

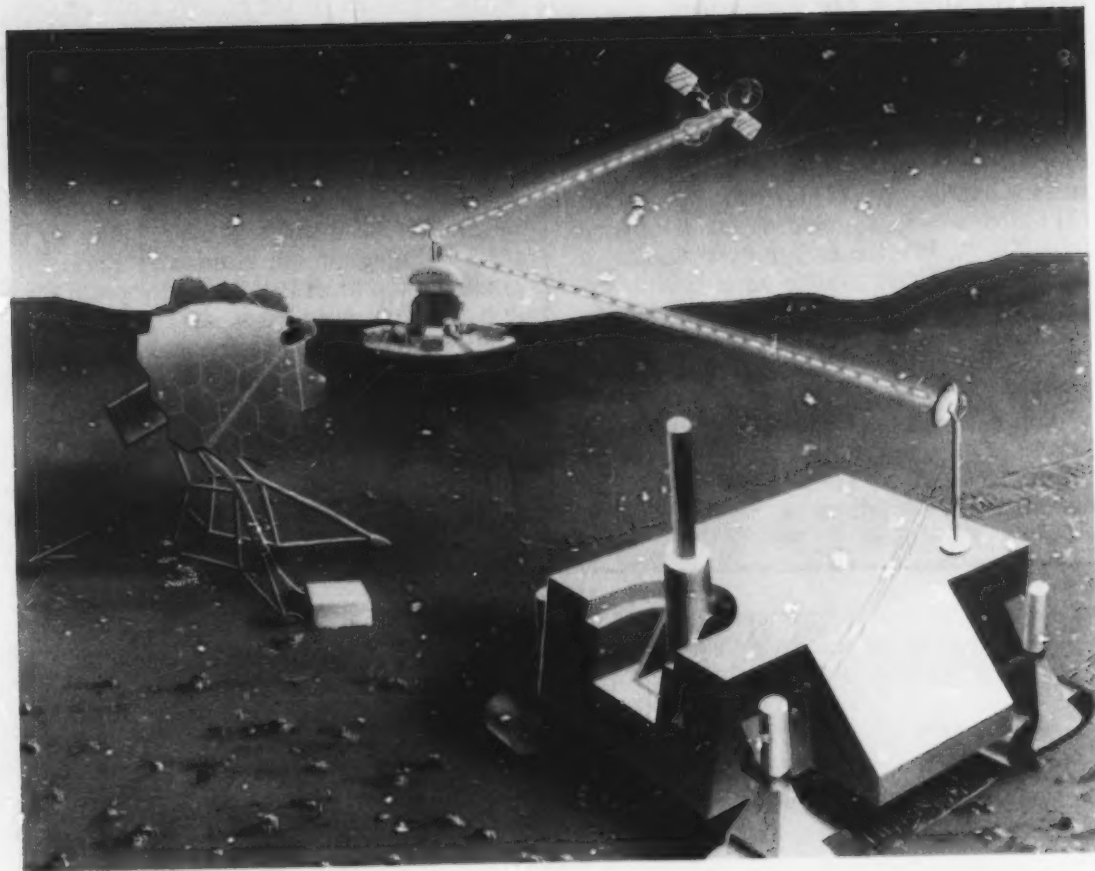
Within each program area (or thrust) are a family of closely related element programs. (For example, the "Planetary Rover" is one of the element programs in the Surface

Exploration program area). Each element program will be implemented by managers at one or more of the NASA field centers. In most cases, one of these Field Centers has been asked to serve as the "lead" for the activity. That leadership responsibility includes providing a technology project manager who will work closely with the NASA Headquarters element managers to plan a strong research and technology effort. A systematic hierarchy of plans is being set in place to integrate the Pathfinder effort, including a top level Pathfinder Program Plan and Sub-Program Plans at NASA Headquarters, and Element Technology Project Plans at the NASA Field Centers.

In the program area and element discussions which are provided in Chapters 2 through 6, the specific NASA Headquarters and Field Center management assignments for the various elements are provided.



Pathfinder



Surface Exploration

Chapter 2

Surface Exploration

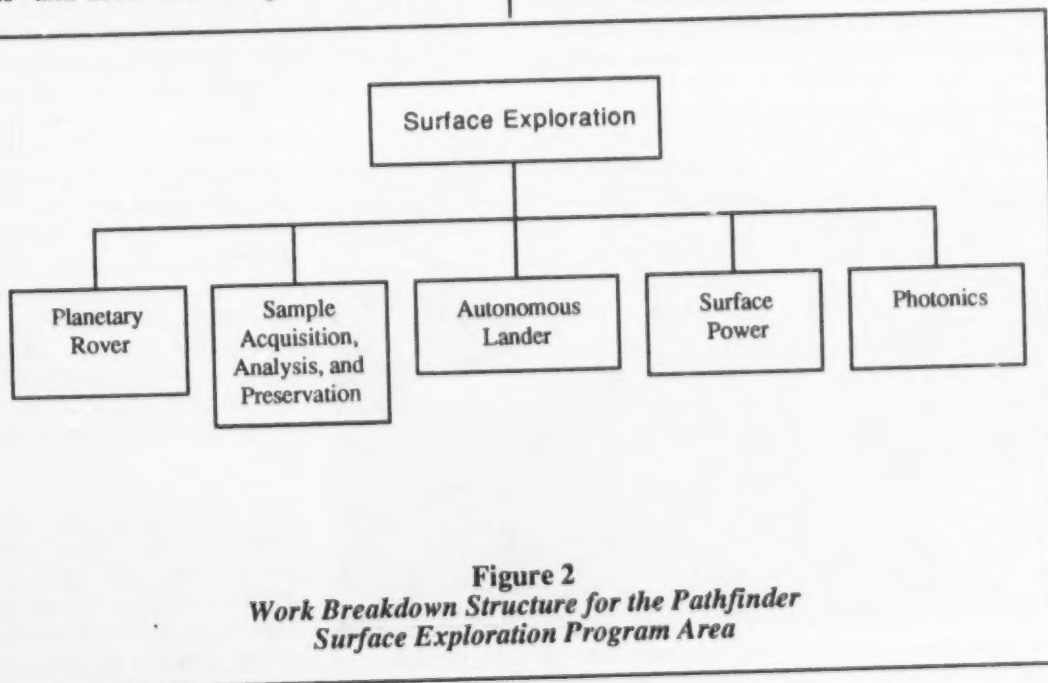
The objective of the Surface Exploration program area is to develop critical technologies to enable or enhance significantly future piloted and robotic exploration of planetary surfaces. The principal focus is on two mission goals: the exploration of Mars, and the beginning of extended human operations on the Moon.

The exploration of planetary surfaces has been an important aspect of Solar System exploration since the 1960s. Robotic precursor spacecraft and piloted Apollo lunar excursion modules (LEMs) visited the surface of the Moon during the first decade of the U.S. civil space program. During the expeditions, a combination of stationary robots and astronauts using "rovers" provided

ed an exciting glimpse of what surface exploration might entail.

During the 1970s, the Viking robotic spacecraft landed safely on the surface of Mars and conducted numerous experiments while orbiting spacecraft provided long term global images of the planet's surface. However, the Viking spacecraft could not move from their landing sites - and the horizon always sat beckoning just beyond the reach of the landers' television cameras and scientific instruments.

The Pathfinder Surface Exploration program area will create the capabilities needed to permit a new era of piloted and robotic planetary surface exploration expeditions. The activity consists of five technology subprograms: (1) Planetary Rover, (2) Sample Acquisition, Analysis, and Preservation, (3) Autonomous Lander, (4) Surface Power, and (5) Photonics.



Each of these subprograms is described in the subsections which follow.

Section 2.1 *Planetary Rover*

2.1.1 Technology Requirements

NASA planning for the future exploration of the Solar System includes both piloted and robotic missions to the Moon and Mars. Most - if not quite all - of the mission scenarios under consideration include the use of mobile surface vehicles to conduct exploration, gather samples, and deploy scientific payloads. Mars rover and sample return mission concepts that are currently under study are one such potential application of "Planetary Rover" technologies. Scenarios involving the creation of human installations require rovers to support both construction and surface mining operations; these systems may be

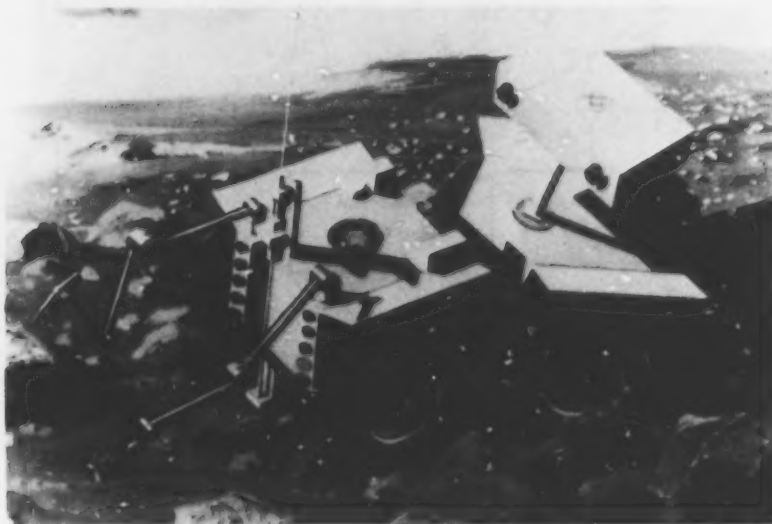
autonomous, teleoperated, piloted, or a variable combination of the three.

Early applications of planetary rovers will be robotic systems with varying requirements for levels of onboard autonomy. Key technologies needed for robotic planetary rovers include surface mobility, local guidance and hazard avoidance, compact and rugged power systems, and a degree of onboard autonomy. The capability to acquire and analyze surface and subsurface samples, to store those samples, and to preserve them for later study and possible return to Earth is key to the success of many planetary rover mission applications. (Those technologies are addressed under the Pathfinder Sample Acquisition, Analysis, and Preservation Program.)

2.1.2 Technology Assessment

There is currently no established program to develop and demonstrate in a systematic fashion the suite of technologies that will be required to make robotic planetary rovers possible. Key technologies that must be considered include (1) mobility, (2) local guidance and navigation, (3) onboard autonomous or semiautonomous operations (including required computational capabilities), and (4) power systems.

No flight-qualified computer technology now exists that will permit a reasonable level of autonomy on a semiautonomous rover. Means of mobility, local guidance and navigation - autonomous



Conceptual illustration of a planetary rover exploring the surface of Mars

and semiautonomous - across unmarked and difficult terrain are at an early stage of development. Some semiautonomous navigation systems have been demonstrated in very controlled environments, but they are not yet suitable for a rover operating in a primarily unstructured and/or unknown environment.

The state-of-the-art in mobile systems is represented by high-speed, all-terrain, vehicles designed for battlefield applications and by experimental vehicles. None of these is designed for long term, low-speed, autonomous operations in very rugged terrain. None have the capability to sense terrain problems (for example, cliffs) and avoid them. Similarly, no automated vehicles exist that are capable of failure recovery operations such as self-righting.

In addition, planetary rover systems must also meet constraints regarding packaging for flight (for example, within the constraints of a planetary aerobraking aeroshell), mass constraints for structures and mechanisms, and deployment from a surface lander.

Low mass, compact power systems capable of driving a mechanically and electronically complex vehicle over rugged terrain do not exist. Modular radioisotope thermoelectric generators (RTGs) which are projected to be the most probable power source for robotic rover applications are being developed under an existing Department of Energy (DoE) program, but the efficiency of planned solid state conversion materials is low.

The technology for semiautonomously identifying, selecting, acquiring, and preparing samples for analysis is at a conceptual stage; no programs currently exist. The state-of-the-art in telerobotic manipulation systems for space applications is represented by the ongoing NASA telerobotics demonstration program, which

is a part of the CSTI program.

2.1.3 Program Description

The long term goal of the Planetary Rover Program is to develop and validate the technologies needed to enable both robotic and piloted exploration of various planetary surfaces. The Planetary Rover Technology Project will establish technology options for a wide assortment of potential future NASA Solar System exploration missions, and demonstrate technology readiness for selected applications. Planetary Rover efforts will encompass piloted, teleoperated, telerobotic, and robotic exploration systems capable of mobility and operations on planetary surfaces.

The near term objectives of this technology project are: (1) development of a solid foundation of systems analyses, technology requirements and planning, and technology validation requirements and plans for the project; (2) establishment of an early national foundation in advanced rover technology concepts (including autonomy, mobility, and guidance); and (3) providing for demonstrated technology readiness for both an early and an evolutionary rover for projected robotic Mars rover and sample return mission concepts.

The near term program will also focus on developing selected key technologies for robotic rovers, demonstrating those technologies - as appropriate - in an integrated testbed, and conducting studies of advanced, high-leverage rover architectures as well as programmatic and technical options for the later development of piloted rover technologies and systems.

The Planetary Rover Program will integrate and extend the Autonomous Planetary Rover work which is being conducted in fiscal years 1988-90 at the Carnegie-Mellon University (CMU) Robotics Institute under

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a NASA OAST grant. The program will also build upon terrestrial programs of the DoD, including DARPA's strategic computing program and autonomous land vehicle program, the VHSIC advanced computing program, and the DoE modular RTG program.

The program will balance research into new, high-leverage technologies such as advanced thermoelectric conversion materials and onboard software for systems autonomy, with focused demonstrations of those technologies and others developed by other NASA and non-NASA programs.

Deliverables

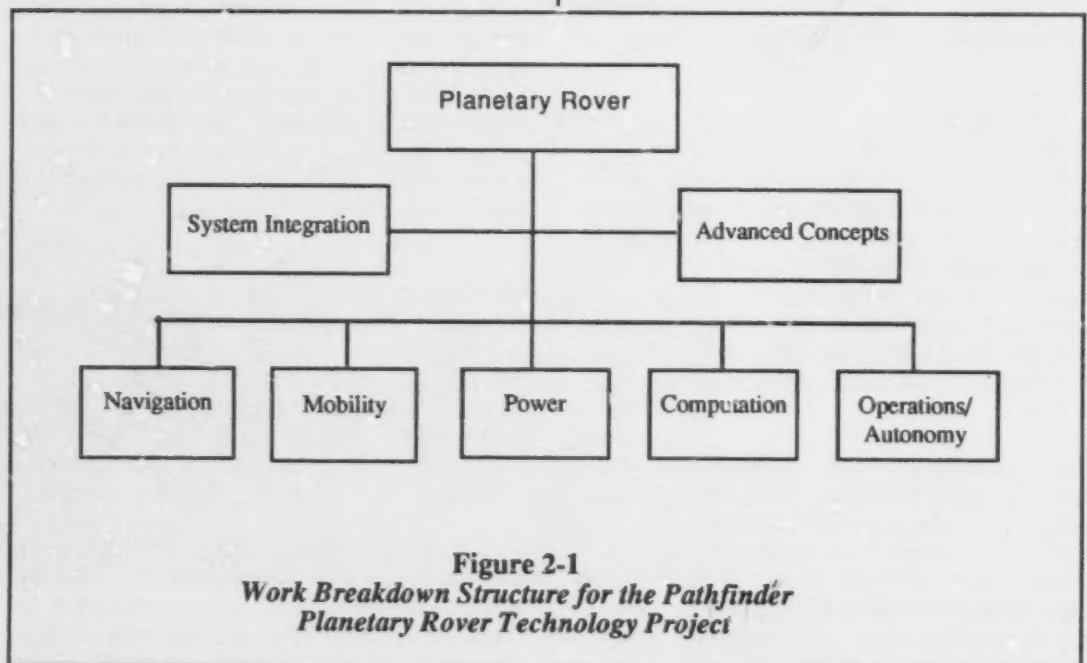
PHASE I. By the early 1990s various concepts for semiautonomous rovers will be proven in order to provide a basis for further technology and mission planning. The current Mars rover and sample return

mission study will provide considerable source material for the formulation of realistic technology performance objectives for the program. Moreover, if an agency decision is made to move forward with a 1998-launched robotic Mars exploration mission program, the Planetary Rover Program may be rescoped.

PHASE II. By the late 1990s, it is projected that the program will consist of two major segments: (1) incorporation of advanced navigation and computation into robotic rovers for increased autonomy, and (2) development of basic technologies and a testbed for piloted rovers.

2.1.4 Organization and Management

Work Breakdown Structure (WBS). The Planetary Rover work breakdown structure (WBS) is directed along technology discipline lines, as well as providing for



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effective management of rover technology demonstration activities. Figure 2-1 provides the WBS for the program.

Management Structure. The overall program will be managed by a Program Manager in the OAST Information Sciences and Human Factors Division (RC). An Assistant Program Manager for Rover Power Systems will be appointed from the OAST Energy, Power and Propulsion Division (RP).

The lead center for the Planetary Rover technology project is the Jet Propulsion Laboratory (JPL). This center will have responsibility for the development of a project plan and for administration of the plan throughout the program. A Technology Project Manager will be assigned at JPL for that purpose. Participating centers include: JPL, the Ames Research Center (ARC), the Johnson Space Center (JSC), the Langley Research Center (LaRC), and the Lewis Research Center (LeRC).

Program Coordination. Planetary Rover efforts will be closely coordinated with OSSA and OEXP. Within OAST, coordination will be maintained with the ongoing CSTI programs in the areas of automation and robotics and with the RM Program Manager for the Pathfinder Sample Acquisition, Analysis, and Preservation Program. A lesser degree of coordination will be maintained with the Pathfinder Photonics Program. General coordination will also be maintained with the DARPA Strategic Computing Initiative, the SDIO advanced computing and Very High Speed Integrated Circuits (VHSIC) programs, and the DoE RTG and Dynamic Isotope Power System (DIPS) programs.

Resources. In order to accomplish the goals and objectives of the Planetary Rover

Technology Project as currently envisioned, resource requirements for the first phase of the program are projected to be approximately \$105 million. The funding allocation for FY 1989, the first year of the effort, will be approximately \$5 million.

Section 2.2

Sample Acquisition, Analysis, & Preservation

2.2.1 Technology Requirements

Sample Acquisition, Analysis and Preservation (SAAP) is a technology program in support of a wide range of future unmanned and manned missions in which extraterrestrial planetary material is to be acquired, analyzed and preserved. The initial focus will be unmanned missions with particular emphasis on supporting the technology needs of a Mars rover mission with sample return to Earth. Although the technologies discussed here are most frequently associated with a rover, they can also be used on landers, ascent vehicles, or other surface traversing systems.

Proposed Mars rover and sample return mission concepts will be taken as representative of an SAAP-oriented mission and will be used to develop a technical focus and general structure for the first five years of the SAAP program. In particular, a Mars rover and sample return mission would use a sophisticated rover to explore an area of Mars and return samples to an ascent vehicle for return to Earth. During traverses, samples in the form of rocks, soil and corings will be collected. A basic requirement is to obtain fresh, unweathered rock. Environmental control including temperature, vibration, radiation, and the like will be required for many samples, especially cores. Once collected, the

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samples may also require onboard preparation such as crushing, sawing, polishing and so on, before analysis or storage. Since the mass that can be returned to Earth is relatively small (approximately 5 kilograms), careful screening and onboard analysis are required to provide the widest range of information about the composition and structure of the planet.

The SAAP subsystem, working in concert with a rover, should have the ability to identify promising sites and locate scientifically interesting surface samples. This will require imaging and ranging instrumentation to provide multispectral data for precise sample location. The SAAP subsystem should have the ability to acquire the desired samples using autonomous systems to generate, pick up and/or drill Martian materials. Once acquired, onboard equipment would process the samples for presentation to instruments or for storage. Instruments will determine the sample's elemental, chemical, and physical properties for transmission to Earth, and in order to make decisions on which samples to keep. The selected samples then must be preserved in pristine condition for delivery to the ascent vehicle. On the ascent vehicle, samples could be analyzed in greater detail and/or stored in a controlled environment for return to Earth.

2.2.2. Technology Assessment

Our knowledge of the Martian surface has not increased significantly since the Mars Viking missions. The Viking Landers provided very good characterization of general terrain features and rock size distributions (within centimeter accuracy), but only within camera view around the landing sites. In addition, detailed surface maps were developed by the Mars Viking Orbiters, but the best resolution obtained from orbit was ten meters. Thus, detailed features of most of the Martian surface are

basically unknown.

Likewise, the state-of-the-art technology for space-qualified, planetary sample acquisition, sample analysis, and sample preservation has also not substantially advanced since the Viking missions. The instrumentation included on the Viking landers were an x-ray fluorescence spectrometer to analyze inorganic matter, and a gas chromatograph mass spectrometer to analyze organic material in the soil. There was no capability to conduct direct mineralogical analysis. Other major limitations included an inability to crack rocks or to take a sample more than a few inches below the surface, and an x-ray fluorescence spectrometer that could only detect elements with atomic numbers greater than 11--thus excluding significant elements such as hydrogen, oxygen, nitrogen, and carbon.

At the present time, there are some new analytical instruments being developed as part of a proposed comet rendezvous mission, the Comet Rendezvous/Asteroid Flyby (CRAF) mission. These include a lightweight spectrometer (about 18 kilograms), which is sensitive to wavelengths between 0.3 and 5.0 microns; a scanning electron microscope/particle analyzer (about 11 kilograms); and a differential scanning calorimeter, which can be used for mineralogical analysis. All three instruments may be adaptable for use on an MRSR mission, but each has its limitations. For example, the spectrometer, although lighter than the Viking instrument, still has the disadvantage of being only sensitive to elements of atomic number greater than 11. Also, the calorimeter is designed for the ballistic penetration of a comet and would have to be redesigned for planetary surface use.

Currently, there is an existing team of specialists actively working to define an MRSR mission more concretely. They are

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addressing such areas as acquisition methodology, instrumentation for analysis, mechanical tools for acquisition, and containment and preservation of samples. However, there is no integrated technology program in place to develop the required capabilities.

2.2.3 Program Description

The Sample Acquisition, Analysis and Preservation subprogram of Pathfinder will develop the technologies required to return to Earth scientifically valuable specimens from a planet's surface and near-subsurface. The SAAP subprogram will concentrate on enabling technologies in the following areas: site and sample recognition and selection, sample acquisition, preparation and processing, sample analysis, and storage and preservation.

To allow the widest range of mission options, the program will produce a technology base that can be applied to a variety of mission scenarios. This will lead to the development of hardware systems that are adaptive, compact, and rugged, and software systems that are intelligent and robust.

Initially, the technology developed in this subprogram will be coordinated with the needs of the Mars Sample Return Mission. The technology needs will be prioritized and only those technology areas which are considered to be enabling will be addressed. The long range objectives will be to address Project Pathfinder's goals of developing the technology which will enable the broadest range of unmanned and manned missions.

An overall SAAP system concept design will also be developed. This activity will be performed in close cooperation with the Planetary Rover subprogram of Pathfinder. SAAP and Planetary Rover technologies may ultimately be integrated to demonstrate

a fully operational technology base.

The following technical approach is being followed for SAAP: (1) determine the technology to be developed in each area, (2) evaluate the technology readiness and criticality, (3) select critical technology areas, (4) determine concepts for developing technology, (5) develop and test concepts analytically and experimentally, and (6) integrate technology disciplines into a SAAP testbed.

The program emphasis for the first 5 years is delineated in the following groupings by priority. It is anticipated that all the primary and secondary elements will be brought together for an overall technology demonstration/validation in the FY1992-94 timeframe. Primary emphasis will be placed on: (1) SAAP system design, (2) site and sample recognition/selection, (3) sample preparation and analysis methods, (4) rock core drilling, (5) sample acquisition tools, and (6) containment concepts. Secondary emphasis will be placed on: (1) long term environmental control, (2) soil coring, and (3) integrated testbed development. These areas will be emphasized more heavily during the second phase of the program. In particular, the testbed will be developed from a laboratory system into an integrated transportable system and used for field experiments in an appropriate Earth-based environment.

Deliverables

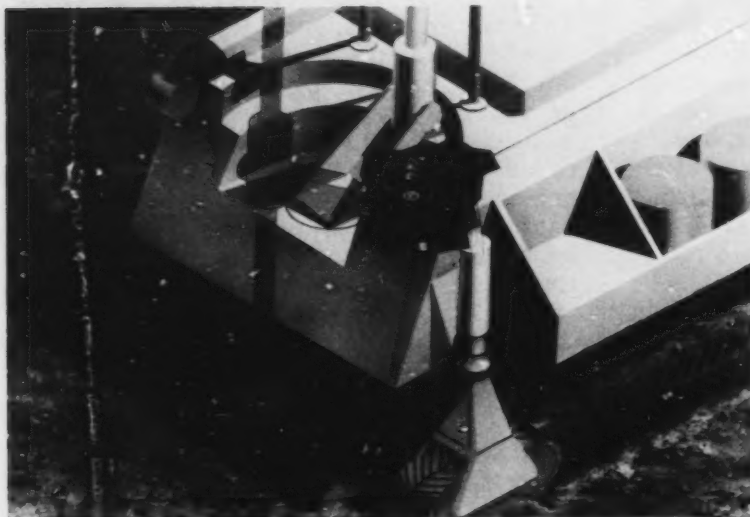
Under this program, sample acquisition, analysis, and preservation technologies will be developed in two phases.

PHASE I. By the early 1990s, key enabling technology concepts will be developed to support late 1990 sample return missions, and to aid in the development of a long-range NASA technology program. An overall SAAP system conceptual design will be developed which will lead to an

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integrated testbed. This will include identifying all key functional elements of a SAAP system, how these elements work together, and the mechanical and operational concepts. In addition, a comprehensive evaluation of the state-of-the-art of each technology discipline will be initiated and new technology will be developed to fill in the gaps. An evaluation of physical, elemental, and chemical analysis methods will be conducted, a concept for a complete

PHASE II. By the late 1990s, concepts and hardware will be developed to the point that work could be initiated on a flight system. Key issues involving space durability (especially in a Martian environment) will be identified and satisfied. A laboratory testbed with realistic operational capability will be developed and tested in an open Earth-based environment to validate systems-level capability of the overall SAAP concept.



Artist's conception of a core sample being analyzed after being obtained from below a planetary surface

sample analysis system will be defined, and concepts to overcome key technology barriers will be developed. Concepts will also be developed for the selection, identification, and acquisition of samples, as well as for containing and preserving the planetary samples so that they may be returned to Earth in a pristine condition. In addition, concepts for specialized tools will be developed for surface and subsurface sample collection such as drilling and coring. Laboratory hardware will be developed for validation in a laboratory testbed environment.

2.2.4 Organization and Management

Work Breakdown Structure. The SAAP work breakdown structure is outlined in figure 2-2. The WBS for the program will consist of five tasks: (1) site and sample selection, (2) sample acquisition, (3) sample analysis, (4) sample containment and preservation, and (5) system design. Site and Sample Selection will focus on developing methods to survey a possible site remotely and identify potential samples for analysis. Sample Analysis will develop technology to enable physical and chemical

instrumentation to be developed for a rugged compact SAAP system and associated methods for assuring efficient use of onboard instrumentation and onboard interpretation of analytical data. Sample Containment and Preservation will develop materials and concepts to assure Earth return of samples in pristine condition. System Design will develop concepts for an integrated SAAP system, and will design and build a SAAP testbed representative of such a system.

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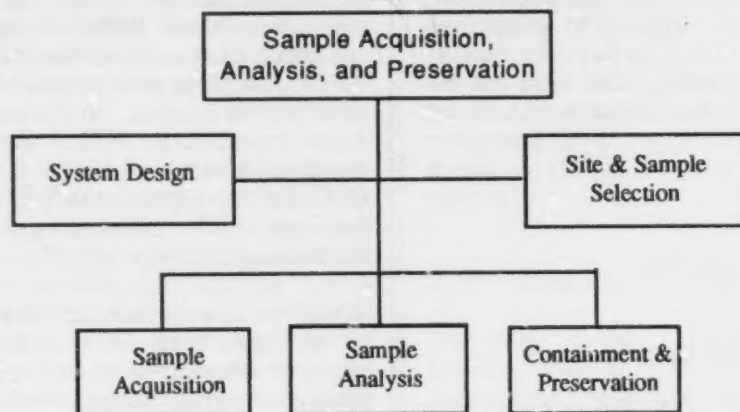


Figure 2-2
Work Breakdown Structure for the Pathfinder Sample Acquisition, Analysis, & Preservation Technology Project

Management Structure. The overall program will be monitored by a Program Manager in the OAST Materials and Structures Division (RM). A technical advisory committee will be established to review the course of planning and progress and to advise the RM program manager. The advisory committee will include members from several OAST Divisions, including RS and RC, and from OSSA and OEXP.

JPL has been identified as the lead center for the program. JPL will appoint an SAAP Technology Project Manager. The Technology Project Manager will have responsibility for technology integration of all activities, planning, and reporting. Other participating centers will include JSC and ARC.

A SAAP Technology Working Group will be created. It will be chaired by the JPL SAAP Technology Project Manager and

will contain members from each participating program center, and from the Pathfinder Planetary Rover Program. The group will be the primary mechanism for coordinating planning for the program, for ensuring that the various elements are technically integrated (especially the Mars rover and sample return mission study and the Pathfinder Planetary Rover Program), and/or for providing technical peer review.

Program Coordination. The program will be coordinated with the ongoing OAST Research and Technology Base program, with the other subprograms of Pathfinder (in particular, with the Planetary Rover Program) with a Mars rover and sample return mission concept, with OEXP, and with OSSA.

Resources. To accomplish the goals and objectives discussed above, the resource re-

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quirements of the Sample Acquisition, Analysis, and Preservation Technology Project have been projected to be approximately \$24 million for the first phase of the program. The funding allocation for FY 1989 will be at the \$1 million level.

Section 2.3

Autonomous Lander

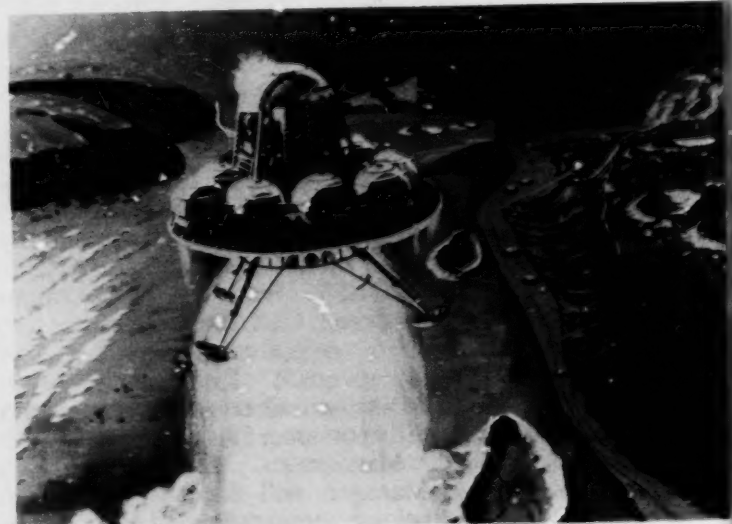
2.3.1 Technology Requirements

NASA's planning for the future exploration of the Solar System includes both piloted and robotic missions to the Moon and Mars. In particular, a robotic Mars rover sample return mission, a piloted expedition to Mars, and the installation of a human outpost on the Moon are all being studied. The success of each of these projects will require the capability to land a planetary exploration spacecraft safely in the face of surface hazards such as rocks and slopes, and accurately, close enough to scientifically-interesting targets to meet mission requirements.

Generic solar system exploration mission requirements associated with surface landings include (1) acceptable levels of risk during landing, (2) non-excessive structural mass needed to survive touchdown in the vicinity of large rocks and steep slopes, and (3) acceptable limits on the operational resources required to survey a target area until an acceptably safe landing site is located. In addition, round-trip-light-time (RTLTL) communications delays will preclude the

use of ground-based control of surface landing operations. In the case of a robotic mission to Mars, RTLTL delays can be on the order of twenty minutes; therefore, the landing on Mars must be made without real-time human control. In the case of piloted Mars expeditions (RTLTL delay approximately 20 minutes) or a Lunar outpost (RTLTL delay approximately 2 1/2 seconds), landings will be made using only local, not Earth-based, human control.

Therefore, approaches considered for lander technologies must be consistent with the rigorous constraints associated with deep space spacecraft; these include constraints on power, mass, volume, and onboard computing capacity. (Within a program, any approach is also constrained by projected schedules for the implementation of these missions.) For example, assuming a Titan IV/Centaur launch vehicle and the



The capability to land precisely and to avoid surface hazards will greatly improve the reliability and returns from future surface exploration missions

use of aerocapture for Mars orbit insertion, a landed mass on the order of 1000 kilograms could be achieved for a Mars rover

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and sample return mission. Clearly, one critical mission requirement will be for the Mars Lander's landing hazard avoidance system to consume only a small portion of that available mass (perhaps approximately 100 kilograms).

In the areas of guidance, navigation, and control (GN&C) mission requirements will necessitate the capability for a precision landing, for example within a 1-kilometer error ellipse around the landing target. Also, local hazard detection and avoidance will be required during the terminal phase of a landing; for example, the final 6 kilometers of altitude and 90 seconds of time during which the lander will utilize a parachute followed by a terminal descent engine to achieve a soft landing.

2.3.2 Technology Assessment

Two robotic Viking spacecraft landed safely on Mars in 1976 without the capability to detect and avoid surface hazards. However, a postmission analysis indicates that there was a nonnegligible probability (>10%) of landing failure due to surface hazards. In the Apollo program, the crew provided onboard, realtime control in case the need arose to avoid a Lunar surface hazard during the final moments of landing.

The Space Shuttle has an "autoland" system; however, it depends on the existence of surface navigation aids. Therefore, although in general NASA has demonstrated a landing capability, it has not demonstrated the technology required for autonomous landers. The technical challenge for Solar System exploration systems lies in detecting an acceptable landing point close to a preselected target site based on limited information, and landing safely there.

In the image analysis technology communi-

ty, many techniques have been developed for detecting objects in images and performing specific processes (such as labeling) on those objects. However, there has been no focus on detecting hazards in realtime and avoiding them via an integrated GN&C system for the purpose of a safe, high-speed landing on a planetary surface.

2.3.3 Program Description

The goal of the Pathfinder Autonomous Lander Program is to develop and demonstrate the technology required to land a planetary exploration spacecraft safely in the face of surface hazards provided by rough terrain, while still landing close enough to the intended target site to meet mission requirements. In order to achieve this goal, the program will be designed to achieve the following objectives:

- (1) Establish mission constraints and requirements,
- (2) Develop and demonstrate the technology required to enable precision landing at a preplanned site, and
- (3) Develop and demonstrate the technology required to enable realtime hazard avoidance during final landing stages. This will require specific advances in the areas of sensors for hazard detection, algorithms for image matching, scene understanding and guidance, and realtime image processing.

The Autonomous Lander Program will follow a general strategy of systems analysis and evaluation using simulation, followed by instrument and algorithm development, followed by demonstrations. The demonstrations will be performed first using a ground testbed and then via simple 1-gravity (1-g) atmospheric flight tests.

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Some initial systems analysis work conducted by a Mars rover and sample return mission study during its current pre-Phase A activities suggests that candidate technical approaches to the safe landing problem may be divided into two classes: first, the "precision landing class," and second, the "hazard detection and avoidance class." The early efforts of the Autonomous Lander Program will be organized on that basis.

The program will begin with the definition of mission requirements and constraints. This activity will cover the full range of missions that will require autonomous landing capabilities, including both Lunar and Mars missions. Initial efforts will focus on the approaches required for the project robotic Mars Rover/Sample Return mission. Mission requirements and constraints will be identified by the end of the first year of the program.

Deliverables

At the end of the first year, work will begin on a relatively simple prototype system that will demonstrate the current state-of-the-art in several critical technologies. This prototype system will be used to better identify the technology areas that need further advancement. Although this approach will provide a focus for early technology efforts, it will not exclude research and development of more advanced techniques that are not yet ready for demonstration.

Development needed to address the two major issues in autonomous landing will also begin in the first year of the technology base. These two areas are (1) precision landing at a preidentified location, and (2) hazard avoidance during the final stages of landing (which can include realtime site selection during the landing process).

Technologies for precision landing at a preidentified location are closer to being state-of-the-art today and will be the first technical area to reach readiness under this program. By the end of the second year, the technology in this area will be demonstrated by simulation. By the third year, technology in this area will be ready for insertion into a testbed for high-fidelity demonstration.

The more challenging and more desirable technology area is the development of the capability to choose the final landing site in realtime. The objectives during this phase of the landing will be to avoid any specific hazards that were not identified prior to site selection, or to maximize the probability of good scientific value for the mission. Technological development to address this issue will require significant advancements in a number of related areas; these include realtime image processing, onboard computing, and sensors for hazard detection. These technologies will be demonstrated in simulators by the end of the sixth year of the program and will be ready for testbeds in the following year.

Flight tests of the techniques that have been demonstrated in ground testbeds will occur in the fifth and eighth years of the program. These flight tests are envisioned as 1-g tests that will demonstrate the techniques, but will require compensation for the Earth gravity. The system that will actually be flown on planetary missions will probably be a combination of both the precision landing capability and the hazard avoidance technologies that will be developed in this program. Clearly, the mission application system will be optimized to make the best use of onboard computing power and prelanding available site information.

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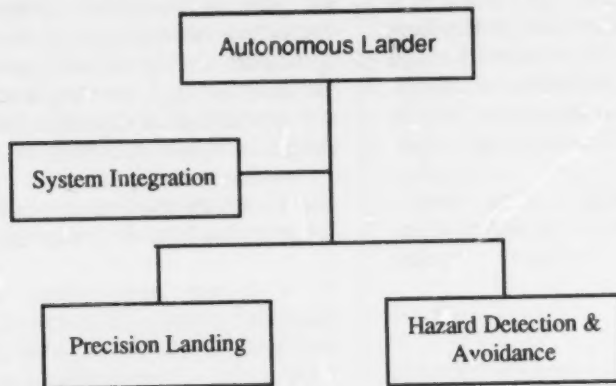


Figure 2-3
Work Breakdown Structure for the Autonomous Lander Technology Project

2.3.4 Organization and Management

Work Breakdown Structure. The work breakdown structure is divided into systems engineering activities and into several classes of issues and approaches to the autonomous landing problem as described in the Technical Approach above; these are Precision Landing and Hazard Detection and Avoidance. The preliminary WBS thus consists of three elements. Figure 2-3 provides the preliminary WBS for the program. This WBS will be revised and refined during the course of the next several months of detailed program planning.

Management Structure. The Autonomous Lander Program will be managed by a Program Manager in the Information Sciences and Human Factors Division of OAST (RC). Program advice and coordination will be provided by the Autonomous Lander Working Group, which is made up of representatives from

the NASA Centers having those NASA Offices who would be potential users of this technology.

The lead center for the Autonomous Lander Technology Project will be JSC. Planning, integration and reporting will be performed by the NASA Center coordinator. Quarterly technology project reports will be submitted to OAST which track progress against Level 1 schedules and identify any problems, issues, or significant accomplishments. Additional NASA centers will be designated as needed to implement specific tasks within the technology project.

Program Coordination. This program will require coordination with the following NASA offices and programs: (1) the piloted exploration mission definition studies of OEXP, (2) development programs for high-capacity, flight-qualified computers being conducted by OAST, (3) the Mars Observer Flight Project being conducted by OSSA,

and (4) the Mars Rover/Sample Return (MRSR) mission study being conducted by OSSA. Coordination with the two OSSA programs is important because of the lack of detailed information about the surface of Mars in the 1-meter object size range, which makes it difficult to assess the degree of hazard at potential landing sites. Coordination with space computing technology developments is also critical because some of the candidate approaches require a realtime, onboard image processing capability.

Resources. Resource requirements for the Autonomous Lander Technology Project for the first phase of the program are approximately \$32 million. The funding allocation for FY 1989 will be \$1 million.

Section 2.4 *Surface Power*

2.4.1 Technology Requirements

NASA's planning for the future exploration of the Solar System includes both piloted and robotic missions to the Moon and Mars. A substantial technology challenge for current and projected space power systems capabilities is the support for human expeditions to the Moon, Mars and its moons, and human operations on the Moon and later Mars. Although the high levels of power associated with an operational outpost - somewhere in the 1000 kilowatt range - will require space nuclear power systems, during the installation of those permanent systems, power systems based on solar energy show the greatest promise. Such relatively small, solar energy-based power systems will also be required as emergency and/or backup power sources.

Low system mass for a given power level is

a critical requirement in order to reduce transportation costs. Another requirement is for appreciable system lifetimes - including dormancy and storage - in order to ensure highly reliable power availability. Relatively high power level requirements are projected in order to support a Lunar outpost of 4-6 astronauts. The projected power output requirement is approximately 25 kilowatts, but may reach 100 kilowatts through modular implementation.

In a Lunar application, the period of darkness extends for two weeks; a Mars application presents a more manageable 12-hour night. Both applications require very high energy density power storage systems. The low insolation on Mars (43% that of Earth), coupled with reduced gravity (1/3 gravity for Mars, 1/6 gravity for the Moon), require high area power density, and low mass power generation systems of a robust design.

The Mars environment (including dust, wind, and a CO₂ atmosphere) and the Lunar environment (including dust, radiation, and wide temperature variations) will require unique design approaches in both power generation and energy storage. That design challenge will be compounded by requirements to provide intermittent operation following extended periods of inactivity.

In addition to the primary application of surface power technologies for piloted Lunar and Mars missions, surface power efforts may also be directed toward power systems in the 1-kilowatt range. Such power systems could be applied in robotic surface precursor missions, or more generally in space vehicles.

2.4.2 Technology Assessment

Regenerative fuel cell energy storage systems offer a twentyfold (20:1) increase

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in specific energy over state-of-the-art electrochemical energy storage technologies in conventional applications. In meeting the long duration storage requirements associated with Lunar applications, this advantage may be even greater. At present, regenerative fuel cell technology is at a low level of maturity. Apollo and Space Shuttle state-of-the-art fuel cell technology is limited to a primary configuration, without regeneration, at a relatively low perfor-

In the regenerative configuration, several design concepts must be evaluated on a system level. Not only must the system performance potentials be identified and quantified, but also the technological barriers to materials compatibility, gaseous and liquid storage and transfer must be identified, quantified, and resolved.

Space power generation via photovoltaic cells has a demonstrable specific power of

about 60 watts per kilogram (W/kg). Recent designs are closer to 130 W/kg. However, the space array concepts associated with these designs have not been developed for surface applications; they require modification - or new concepts - for evaluation of potential applications in the non zero-gravity conditions on the Lunar and Mars surfaces. Photovoltaic cell and blanket technology advances that improve the state-of-the-art 2-mil silicon technology will contribute significantly

to the 300 W/kg photovoltaic array goal. Amorphous silicon, primarily a terrestrial technology, has been fabricated on flexible substrates and is compatible with low volume storage requirements for space applications. Performance must be upgraded to meet surface power requirements for stability, longevity, and high efficiency.

In general, power generation via advanced solar dynamic technologies appears to offer no mass advantage over advanced photovoltaic systems. However, the potential



Astronauts laying out a photovoltaic array on the surface of Mars

formance level. Increasing the operating temperature by means of increased current density will improve performance, yet the oxygen electrode catalyst - a critical component in a fuel cell stack - has not been developed to withstand lengthy high temperature (250°F) operation. Commensurate with the need for higher temperature operation are requirements for efficient and reliable thermal, gas, and liquid management technologies in the regenerative configuration. Bifunctional catalysts, if proven viable, will greatly reduce the complexity and mass of a regenerative fuel cell.

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advantages of obtaining processed heat as a by-product, the state of maturity of solar dynamic systems, their scalability, and their packageability demand evaluation of the technology barriers peculiar to surface missions. The concentrator, heat receiver, and energy conversion system may be affected adversely by the Lunar or Mars environments as well.

Photovoltaic power generation historically has relied on electrochemical energy storage technologies. However, solar dynamic power systems have traditionally utilized thermal energy storage techniques. The latter will require modified approaches - including the use of regenerative fuel cell electrochemical energy storage - in order to meet the lengthy dark periods associated with surface operations. Replacing thermal energy storage systems with electrochemical energy storage will permit a substantial reduction in solar dynamic system mass. Hence, there is a potential fivefold (5:1) improvement in specific power for photovoltaic arrays and a threefold (3:1) improvement for solar dynamic systems. These technological advances would result in a substantial mass savings for either a Lunar or Mars surface application.

2.4.3 Program Description

The objectives of the Surface Power Program are to develop a technology base that will support the development of space power systems capable of delivering tens of kilowatts of user power, thereby enabling future human space operations. The goal is to provide Lunar surface operations power, start-up power for a main outpost power system, piloted Mars expedition surface power, and power for Phobos and/or Deimos operations.

In cases of sustained base operations, it is anticipated that the startup solar power system will later serve as an emergency power

source for the expected nuclear power system. To accomplish these objectives, appropriate solar-based technologies will be developed to a sufficient level of technology readiness to assure confidence in the various potential mission applications. Breadboard verification of key component technologies will be followed by ground-based system verification tests of integrated power generation and energy storage technologies. It has been determined that the highest potential for successfully achieving demonstrated surface power capabilities lies in the development of power generation systems utilizing either photovoltaic or solar dynamic technologies. Due to the length of the dark period on the Lunar or Martian surfaces, both power generation approaches dictate the use of regenerative fuel cells for energy storage.

The near term program will include systems analyses based on various mission scenarios for both Mars and Lunar surface applications; these will result in trades and concepts for potential system designs. These systems analyses will systematically develop surface power technology requirements, including critical technology barriers, that will be used to help guide subsequent program planning.

The program will address energy storage technology, with the focus on regenerative fuel cells. It will encompass several component technologies, including development of high temperature oxygen electrode catalysts in conjunction with lightweight, high temperature structure components. Gas, liquid, and thermal management innovations will be evaluated against the goal of reducing complexity while increasing life. Emerging lightweight, robust tank technologies for gaseous reactant storage, and an enabling technology for very high energy density regenerative fuel cells, will be evaluated. Selected ground-based breadboard evalua-

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tions will be used to validate the system performance potentials of critical components.

Efforts in amorphous silicon photovoltaic cell technology will be directed at increased efficiency, reduced mass, and improved lifetime and reliability. Blanket and interconnection technology advances will be developed. Array concepts, derived from current technologies and concepts, will be evaluated leading to key critical component fabrication and validation with promising, available, and appropriate cell and blanket technologies.

Solar dynamic power generation efforts will be limited to studies and critical technology verification as appropriate. The studies will focus on identifying technical barriers resulting from a novel systems approach in unique Lunar or Mars environments. These technical barriers to a viable solar dynamic power generation system will be evaluated in light of ongoing programs in concentrators, receivers, and energy conversion systems.

Deliverables

PHASE I. Promising technologies, as well as systems to be pursued, will be guided by system and mission analysis to be completed in the first eighteen months of the program. By mid-1991, promising energy storage component technologies will be identified with breadboard verification completed by 1993. Prototype blanket technology will be verified by 1994. Key prototype array components under fabrication by 1993 will reflect promising design concepts that have been previously evaluated.

PHASE II. During Phase II, and by the mid to late 1990s, a prototype testbed power system using outputs from Phase I of the program will be fabricated. Power

generating and energy storage systems will be built and integrated into power systems and tested to verify design concepts for future flight hardware fabrication.

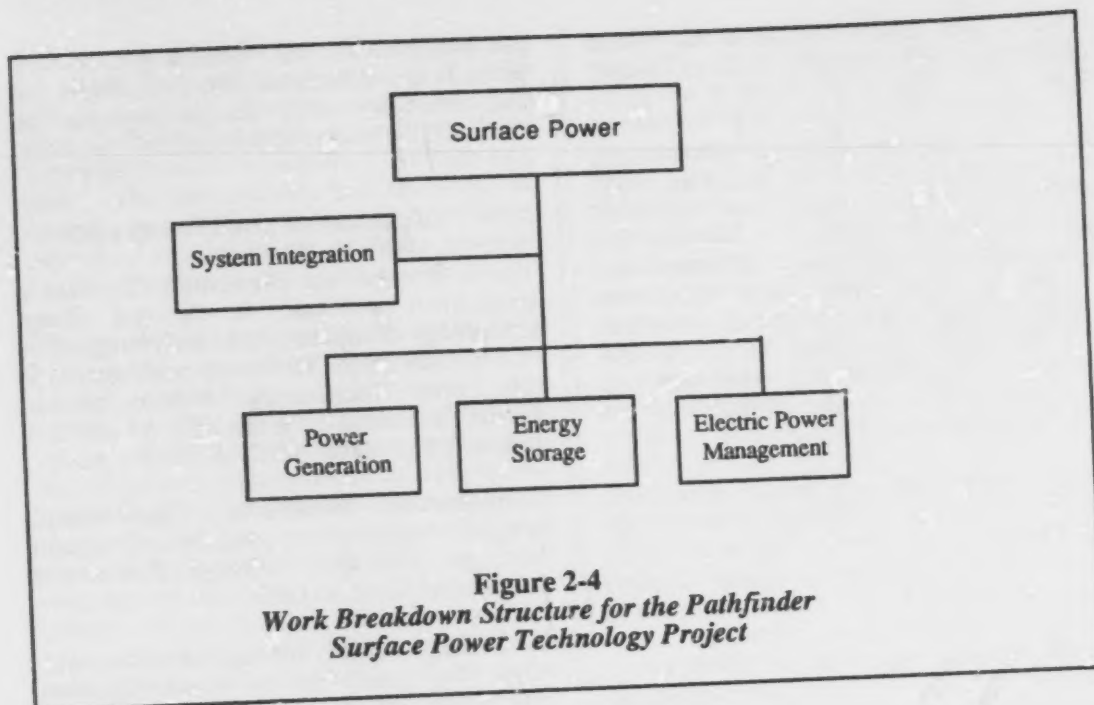
2.4.4 Organization and Management

Work Breakdown Structure. The work breakdown structure is directed along technology discipline lines, with integration and coordination functions performed by the Power Technology Division at the Lewis Research Center (LeRC). Figure 2-4 provides a top level WBS for the program.

Management Structure. The overall program will be managed by a Program Manager in the OAST Energy, Power, and Propulsion Division (RP).

Technology Project management responsibility will reside in the Power Systems Integration Office at LeRC. The program manager will have the responsibility of coordinating with other programs and Pathfinder subprograms to avoid duplication of efforts and to ensure that all technologies are being adequately addressed. The Technology Project Manager will have responsibility for leading the development of a technology project plan and for the implementation of the project throughout its duration. All participating centers will be responsible to the Technology Project Manager for all matters, including resources, project responsibilities, and administrative duties pertaining to reporting, schedule, and milestones.

The Technology Project Manager will also have the responsibility of insuring that specific technology efforts are coordinated through matrixed responsibilities in each technology discipline. The project manager will utilize discipline branches within the LeRC Technology Power Division as well as expertise available in the LeRC Advanced Space Analysis Office, the Jet



Propulsion Laboratory, the Johnson Space Center, and other NASA Centers as appropriate.

LeRC will have responsibility for leading the development of a Technology Project Plan and for administration of the plan throughout the program. All participating centers will be responsible to the program manager in RP for all questions involving resources and program responsibility. They will be responsible to the lead center in administrative matters pertaining to reporting, scheduling, and milestones.

Program Coordination. The Surface Power subprogram of Pathfinder will be coordinated with other appropriate programs established in the OAST Space Research and Technology (R&T) Base program, in the Civil Space Technology Initiative (CSTI), and with other subprograms of Pathfinder. Mission scenario de-

velopments will be coordinated with the Office of Exploration. Technical advances realized by the Space Station program and non-NASA space programs will be incorporated into overall program planning as appropriate.

Resources. Resource requirements for the first phase of the program are approximately \$36.5 million. The funding allocation for FY 1989 is \$1.5 million.

Section 2.5 Photonics

2.5.1 Technology Requirements

NASA's planning for the future exploration of the solar system includes missions requiring both extremely powerful infor-

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mation processing systems, and computers and networks with a high degree of fault tolerance. The emerging technology of photonics can play a key role in meeting these needs. The Pathfinder Photonics program is aimed at the development of key enabling systems and device technologies that have the most leverage on future NASA needs.

The four leadership initiatives in the Sally Ride report, *Leadership and America's Future in Space*, impose a variety of taxing requirements on information acquisition and processing capabilities in space. For instance, the control and communication systems of transport vehicles carrying humans, or of Lunar or Martian habitats, must be extremely reliable. The functions invoked to achieve fault tolerance exact a high overhead in hardware and software which has a negative impact on processing and communication rates. For human transport vehicles and habitats for Pathfinder, control and communication systems using conventional electronics and cabling cannot provide the necessary systems performance within the needed weight and power margins. Fiber optic networks with compatible computing and sensing nodes and in situ integrated optic sensors will enable the necessary overhead to be accommodated while substantially reducing system power, mass, and volume, and increasing processing and transmission capacities by several orders of magnitude.

NASA also has a number of needs for processing where a very high degree of parallelism is involved, such as two-dimensional image processing. Extraction of information from an optical image, laser ranging data, and multispectral data is needed to facilitate the intelligent exploration of the surface of both the Moon and Mars with a robot roving vehicle able to discover sites of potential mineralization, to recognize anomalous rocks and other potential surface samples, and to negotiate

rapid traverses of the surface without hazard. Similarly, very fast information extraction is critical to facilitate the last few minutes of the powered descent of a robot lander to a desired landing spot identified from orbital imagery. In these cases, correlations and feature extractions must be implemented over an entire image, and the capability of optical processing to execute images in a million parallel channels is extremely powerful. Additionally, a planetary rover/orbiter communication system may demand phased array radar with hundreds or thousands of transmitter chips. This may be difficult to do in space without the development of photonic controls.

2.5.2 Technology Assessment

At present, optical processing systems have achieved very limited application in ground and space systems. They have been used for processing synthetic aperture radar data on the ground for NASA space missions, and they are being planned or developed for high-speed RF spectrum analyzers for both ground and space use. Photonics technology does have the potential, however, to surpass electronics in important areas of computation. The high throughput of analog photonic data processing reflects the enormous information capacity of light waves and the inherently concurrent nature of wavefront operations.

Photonic flight systems are expected to be more fault-tolerant and reliable than comparable electronic systems because they will have fewer discrete active components and physical interconnections, and architectures inherently more resistant to single-component failures. Photonics are still immature as a technology for NASA flight systems. However, the performance of matrix multiplications, correlations, convolutions, broadband spectrum analy-

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sis, and other basic mathematical transformations has been demonstrated in the laboratory and in prototype applications, and research is rapidly broadening the scope and power of these operations. The potential to package optical information systems in forms compact and robust enough for qualification and deployment has been established. The challenge for NASA is to develop the specialized processing algorithms, the fault-tolerant architectures, and the physical components needed to focus the technology on future flight-system requirements.

The Photonics Program will address future mission requirements that do not appear to be fulfilled by current information processing capabilities. Present high-capacity, fault-tolerant, fiber optic networks employ interface devices to transfer the optical signal to an electronic signal and back again. This conversion process causes a data bottleneck to occur at the network nodes. By processing the information optically, the light would be allowed to continue undeterred unless a fault were detected. Current in situ sensors for spacecraft typically do not fulfill the sensitivity and lifetime requirements of planetary missions. Current designs of electronically controlled phased array antennas appear to be too bulky and heavy for space-based use. Finally, many image processing calculations needed for both autonomous landers and rovers are so computation-intensive as to require large earthbound computers.

2.5.3 Program Description

The strategy of the program consists of focusing the technology effort in the first few years of the program through a combination of breadboard testing and systems studies (to be performed in part by the Office of Exploration) that will result in a few

systems that will be developed to the prototype stage in order to compare their performance with more traditional electronic systems. The Photonics program will encompass both systems and device activities which are at present at varying stages of technology readiness. The program includes basic research in photonic devices which will be focused on the class of devices known as Spatial Light Modulators (SLMs) and photonics system developments which will include initial demonstrations with existing SLM technologies, followed by demonstrations with the new SLM technologies during later phases of the program.

The Pathfinder Photonics Program will develop those hybrid photonic/electronic technologies that have the potential to be better than all-electronic systems for solving some of the mission requirements for NASA's future planetary missions. Specific objectives of the program are as follows:

- 1) To develop fault-tolerant, high data rate networks for space systems applications. These applications include autonomous spacecraft, interplanetary transport vehicles, and planetary and lunar habitats. Goals include the development of photonic nodes and in situ integrated optical sensors.
- 2) To enable safe traverses by a planetary rover at higher speeds and requiring less power than competitive all-electronic systems through the use of optical pattern recognition. The program will provide a capability for the high speed acquisition and analysis of reconnaissance data acquired by a planetary rover through the use of optical multispectral processors. Additionally, the program will provide Ka-band phased array radar for rover/orbiter communication at potentially much lower mass than competitive electronic systems through the use of fiber optic control.
- 3) To enable the electronic vision systems

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needed for automated landing on planetary surfaces to have up to three orders of magnitude reduction in processing requirements through the use of a photonic preprocessor. Critical technologies will be developed in photonic sensors, integrated optical switches, fiber optic control of MMIC chips, and image processing architectures. Selected spatial light modulators (SLM) will be developed to enhance the processing speed of the above systems during later phases of the program. Many of these tasks will leverage photonics work currently being accomplished by the DoD, industry, and universities. The ultimate program objective is to test these systems with mission simulated data and testbeds when available.

The program begins with breadboard testing of a variety of hybrid photonic/electronic technologies that have the potential to fulfill mission requirements as developed by mission analyses. The technologies fall roughly into three categories: fault-tolerant networks which include photonics switches and sensors; SLMs which include semiconductor and other materials and device development; and optical processors which utilize light's two-dimensional, parallel, noninteracting propagation capabilities for optical computing. By the end of 1990, the three thrust leaders will review their efforts in order to downselect the technologies mentioned above to those few that have the most potential to fulfill mission requirements.

In the early 1990s, the United States will make a decision on which mission to pursue. That decision will be based partially on which technologies are mature enough at that time to support that mission. For this reason, the Photonics program will continue breadboard development of those systems that were downselected in 1990, and will perform an evaluation of their performance in 1992 in order to support NASA's decision. In the Fault-Tolerant Networks

thrust, this will involve the development of those photonic architectures, devices, and sensors necessary to support the goal of building a network that can withstand three faults while having a data throughput of up to 1000 Mbps. In the Autonomous Planetary Systems thrust, this will involve the development of a variety of optical processors.

Vision systems will be developed for both autonomous lander and autonomous rover applications. Initial testing will be done using simulated data in order to compare the optical computers' performance with that of electronic computers. An optically controlled phased-array antenna will be developed for rover/orbiter communication. Similarly, in the Spatial Light Modulator thrust, those few SLMs that were downselected in 1990 will be developed to mature, prototype devices through the year 1995.

Throughout the late 1990s, focused development and final testbed evaluations will occur utilizing updated mission studies. The SLM development will have resulted in good candidates for insertion into the vision and node processing systems, thus dramatically increasing processing capability. The Fault-Tolerant Networks thrust will have maximally leveraged the CSTI/Data subprogram work in optical switches, as well as DARPA's photonics program to build space-qualifiable, high-capacity, fault-tolerant networks including in situ sensors that have been tested in an integrated data systems testbed. The Autonomous Planetary Systems thrust, together with the Autonomous Lander and Rover subprograms of Pathfinder, will have coordinated development of space-qualifiable, photonics/electronics vision system prototypes which will undergo final evaluation on the rover and lander testbeds. By 1998, the systems will be developed into prototypes and coordinated with other Pathfinder demonstrations for final

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verification.

2.5.4 Organization and Management

Work Breakdown Structure. The program is organized into three thrust areas, with specific integrating, or cross-cutting tasks (see Figure 2-5). A continuing program of systems studies will be pursued to guide the overall direction of the effort. In the second year of the program, a downselect of tasks will be undertaken and a limited number of tasks will be selected for prototype development.

Management Structure. The Photonics Program is managed by the Photonics program manager in the OAST Information Sciences and Human Factors Division (Code RC). Responsibility for Center assignments, project plan approval, and funding allocation will remain at

Headquarters Code RC. Program advice and coordination is provided by the Photonics Working Group, which is made up of representatives from the NASA Centers and those NASA Offices that would be potential users of the technology.

Project planning, integration and reporting is performed by the NASA Center thrust leaders and the Photonics Working Group co-chairperson. Quarterly project reports will be submitted to OAST, tracking progress against Level 1 schedules and identifying any problems, issues, or significant accomplishments. NASA Centers will be designated to implement project elements.

Program Coordination. The program was originally formulated with the guidance of the Ad Hoc Review Team on Photonics subcommittee of the OAST Space Systems Technology Advisory Committee. This

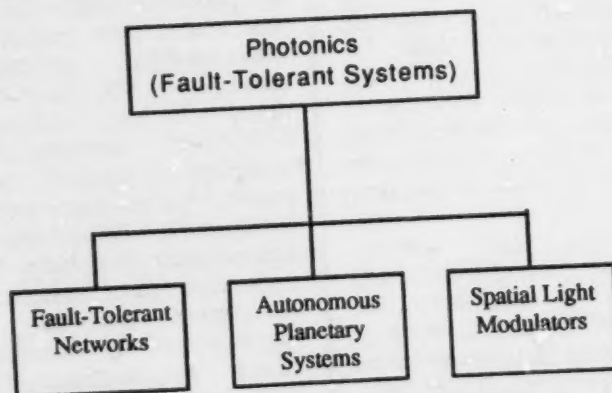


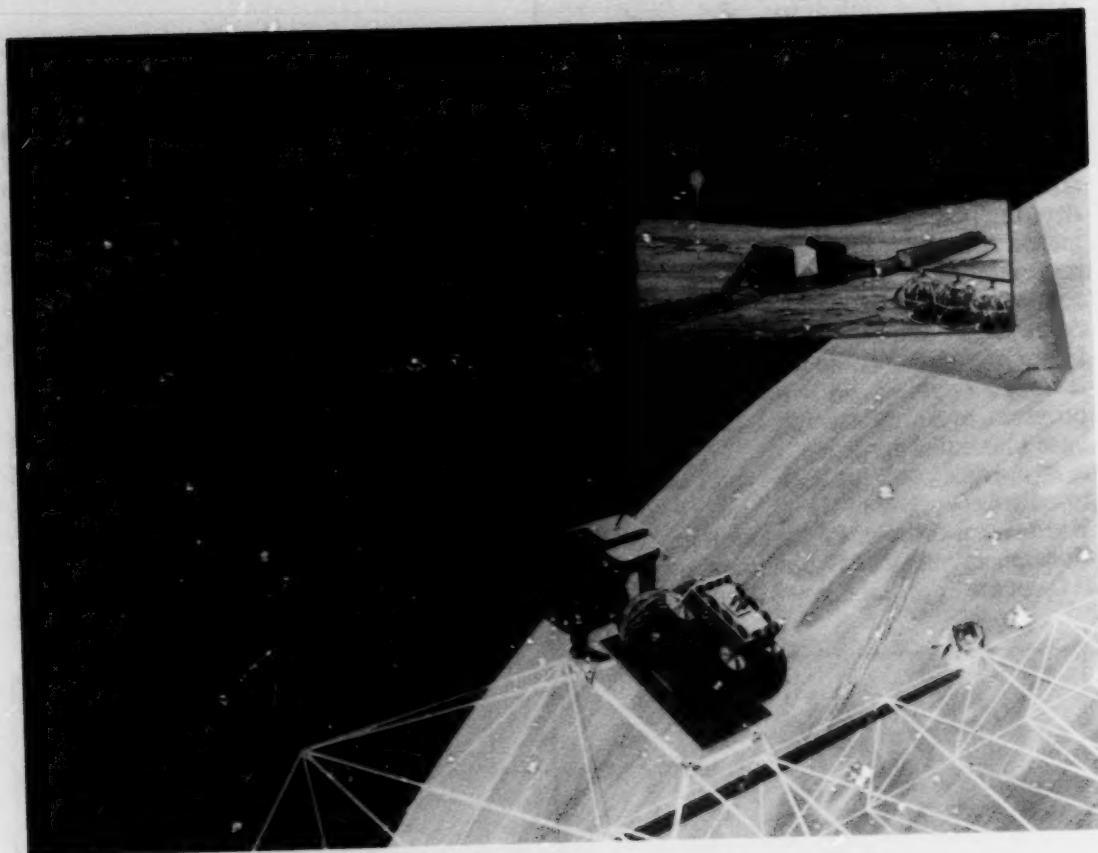
Figure 2-5
Work Breakdown Structure for the Pathfinder Photonics (Fault-Tolerant Systems) Technology Project

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Review Team facilitated the coordination of the NASA program with DARPA, Air Force, Army, universities and industry. In addition, this program will be coordinated with those subprograms of Pathfinder which are customers for Photonics technology including Planetary Rover, Sample Acquisition, Analysis and Preservation, Autonomous Rendezvous and Docking, and Autonomous Lander. In addition to the internal coordination in Pathfinder, interaction will also take place with the representatives of science instrument users in the Office of Space Science and Applications and the Office of Exploration. Finally, the Photonics program will leverage ongoing work in the CSTI Data program, and the Research and Technology base Photonics program.

Resources. Resource Requirements for the first phase of the Photonics Technology Project are approximately \$32 million.

Pathfinder



In-Space Operations

Chapter 3

In-Space Operations

The objective of the In-Space Operations program area is to develop a wide assortment of key technologies that will enable or significantly enhance high-leverage space operational capabilities in support of solar system exploration.

Advances in our capabilities for in-space operations have been a major objective of the civil space program since the 1960s. For example, a significant part of the Gemini Program's objectives was the development and demonstration of orbital rendezvous and docking - a key capability for the Apollo missions to the Moon.

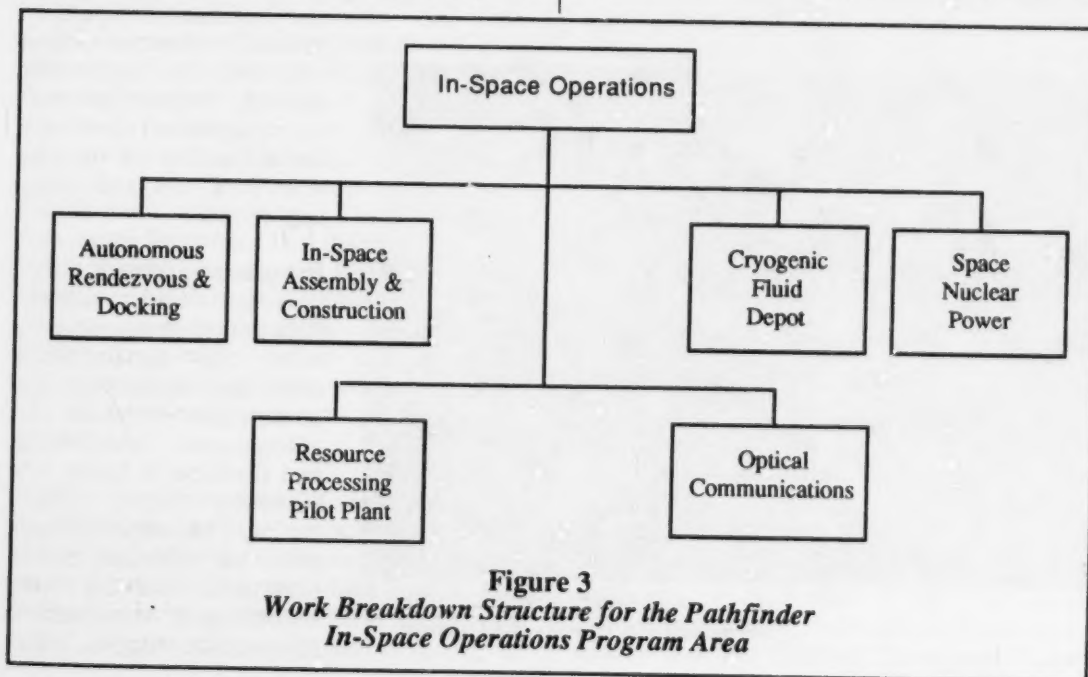
The Space Shuttle provided a major augmentation of U.S. in-space operations capabilities. The Shuttle has demonstrated critically-needed operations, including retrieval

and repair of spacecraft in space, as well as providing a platform for extended technology demonstrations such as in-space construction techniques, space power systems, and microgravity fluids research.

Space Station *Freedom* will provide still another major enhancement of our capabilities by providing a permanent in-space facility. Operations will include spacecraft servicing, microgravity research, and staging of future missions. In fact, each stage in the history of the civil space program has been dependent upon technological advances in the area of in-space operations.

Pathfinder In-Space Operations efforts consist of six technology projects: (1) Autonomous Rendezvous & Docking, (2) In-Space Assembly and Construction, (3) Cryogenic Fluid Depot, (4) Space Nuclear Power, (5) Resource Processing Pilot Plant, and (6) Optical Communications.

Each of these is described in some detail in



the subsections which follow.

Section 3.1

Autonomous Rendezvous & Docking

3.1.1 Technology Requirements

NASA's planning for the future exploration of the solar system includes both piloted and robotic missions to the Moon and Mars. As was true with Apollo, these missions will require the use of smaller vehicles to go to and from the lunar or planetary surface. Because of round-trip-light-time (RTLTL) delays in deep space communications, realtime Earth-based control of these vehicles will be impossible.

The capability for autonomous rendezvous and docking with the mission elements remaining in orbit will be required for both

piloted and robotic missions.

The specific technology requirements include the development of sensors and mechanisms, trajectory control requirements and techniques for operations in Lunar and planetary orbits, and associated integrated guidance, navigation, and control algorithms such as automatic selection/execution/recovery techniques and multivehicle cooperative control.

Sensors are required to provide long- and short-range tracking and relative navigation from several hundred kilometers down to the contact point of docking. Sensor technologies are driven by performance requirements for extended service life in hostile environments with long periods of dormancy. Docking mechanisms will support robotic vehicle operations.

Trajectory control techniques will differ from current Earth-orbit, piloted vehicle operations in that many of the constraints, such as lighting, ground tracking coverage, and continuous space-to-ground communications will not be applicable. Instead, trajectories must be designed to maximize the reliability of rendezvous in Lunar and planetary orbits.

Integrated guidance, navigation, and control (GN&C) designs must provide the performance, reliability, autonomy, and automation required for autonomous rendezvous and docking in Lunar and planetary orbits. Major design challenges include automatic selection, execution, and recovery techniques and multivehicle cooperative control. Ex-



A fuel-carrying vehicle docks autonomously with a future space station

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pert system technologies are applicable.

3.1.2 Technology Assessment

At present, the United States has not demonstrated an autonomous rendezvous and docking capability. Current capabilities require extensive ground and flight crew participation. The rendezvous phase of a mission is based on significant ground tracking of the spacecraft. The docking phase requires the control of an observer on one of the spacecraft. This degree of observation will not be available for robotic Mars vehicles and the communication time delays will preclude control through teleoperation from ground-based operations centers. The implementation of autonomous rendezvous and docking will require the development of several critical technologies.

Sensors for long- and short-range navigation must be developed which provide the required performance, meet constraints on mass, volume, and power, and can withstand the hostile environment and long periods of dormancy associated with planetary exploration mission. The onboard rendezvous sensors on the Space Shuttle (star tracker and rendezvous radar) provide relatively poor performance and require careful crew monitoring. They are totally inadequate for ranges less than 90 feet. The radars being considered for the Orbital Maneuvering Vehicle (OMV) will also be ineffective at very close ranges. No suitable long-range radars that meet the power, mass, and performance requirements of a Mars rover and sample return mission are available.

A prototype laser docking sensor is being developed for a flight experiment in FY 1991. This system shows much promise for ranges from zero to greater than three miles. Further work is needed to study extensions of the range of this sensor and reducing its

power, mass, and volume requirements. Other candidate sensors such as millimeter-wave radar and robotic video image recognition systems require further evaluation and technology development.

GN&C algorithms for the rendezvous problem are well understood, but work is required to focus the designs on mission constraints unique to solar system exploration scenarios. Current designs focus on constraints associated with piloted vehicles and include lighting conditions and continuous space-to-ground communications. Solar system exploration missions will not necessarily be subject to these constraints, but require an emphasis on reliability of the rendezvous and docking operations. Cooperative control and automatic selection, execution, and recovery are major design challenges.

Docking mechanisms for piloted vehicles have been or are being developed which should suffice for piloted solar system exploration vehicles. However, unique mechanisms will have to be developed for small, robotic vehicles such as a Mars Ascent Vehicle and a Mars Orbit Vehicle that are being planned as elements of a robotic Mars mission. In addition, the docking mechanisms for solar system exploration missions will require extended service life in hostile environments with long periods of dormancy, high system reliability, and high levels of autonomy for robotic vehicle operations. The mechanisms will be subject to severe power and mass restrictions.

3.1.3 Program Description

The objectives of this program are the development and demonstration of the enabling and enhancing hardware and software technologies, and technical approaches for autonomous/automated rendezvous and docking, to support Lunar

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and Mars missions. Specifically, the constraints and unique requirements will be established for the various types of planetary missions that are envisioned. Using these requirements and constraints as guidelines, long- and short-range sensors will be developed for rendezvous and docking. Algorithms will be developed for both long- and short-range phases of the rendezvous problem and will be demonstrated in computer simulations and then in flat floor testbeds. Finally, flight tests of the rendezvous and docking concepts developed under this program will be planned.

For the several selected solar system exploration mission scenarios and corresponding vehicle configurations, coordinated systems-level rendezvous and docking requirements will be defined. The performance requirements on the autonomous rendezvous and docking hardware and software will be established.

The hardware and software technologies needed to meet those requirements will be identified, and current technologies will be assessed for applicability. The need for new technologies will be defined with an emphasis on sensors for long- and short-range tracking and relative navigation. A decision will be made as to whether a single sensor or a suite of sensors will most efficiently meet long- and short-range performance requirements for Lunar and planetary missions.

Trajectory control requirements and techniques for autonomous rendezvous and docking will be defined. Candidate GN&C designs will be developed to implement these capabilities. Six and twelve degrees of freedom (DoF) simulations will be developed and used for performance, dispersion, and sensitivity analyses and trade studies of these designs.

Results of these evaluations will be used to establish the specifications for prototype sensors. Prototype sensors and hardware and software emulations will be developed and incorporated into testbed proof-of-concept demonstrations. The requirements and benefits of technology flight demonstrations will be evaluated.

Deliverables

The requirements and mission constraints for autonomous rendezvous and docking for the various planetary missions will be established during the first year of the program. In addition, work will begin on the GN&C concepts that are most appropriate for this problem and on sensors that are required for the long- and short-range parts of the problem. There will be two sets of demonstrations of the technology based on near and far-term capabilities.

The near term demonstrations will begin in the second year of the program with computer simulations of GN&C concepts and with the flight test of the Laser Docking Sensor (which is already scheduled and is independent of this Pathfinder effort). High fidelity simulations will begin in the third year of the program with a transition to flat floor demonstration the following year.

The more advanced sensors will be demonstrated in the fifth year, and will be added to the computer simulations and then to the flat floor testbeds by the seventh year of work. Flight demonstrations must be carried out in orbit and are beyond the currently project funding level of this sub-program of Pathfinder. This program will carry the technology to a stage where it is ready for flight demonstration.

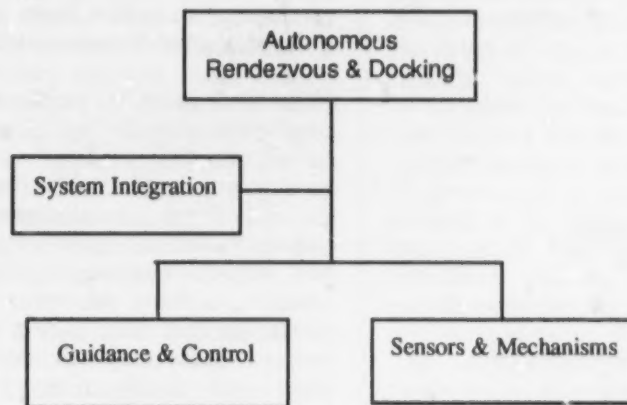


Figure 3-1
*Work Breakdown Structure for the Pathfinder
Autonomous Rendezvous & Docking Technology Project*

3.1.4 Organization and Management

Work Breakdown Structure. The work breakdown structure is directed along technology discipline lines. It consists of three major areas: systems integration, guidance and control, and sensors and mechanisms. Figure 3-1 provides a preliminary WBS for the program.

Management Structure. The overall program will be managed by a Program Manager in the OAST Information Sciences and Human Factors Division (RC). Responsibility for Center assignments, project plan approval and funding allocation will remain at OAST/RC. Program advice and coordination will be provided by the Autonomous Rendezvous and Docking Working Group, which is made up of representatives from the NASA Centers and those NASA Offices that would be potential users of this technology.

Technology Project planning, integration, and reporting will be performed by the NASA Center coordinator. Quarterly project reports will be submitted to the OAST Program Manager, tracking progress against Level 1 schedules and identifying any problems, issues, or significant accomplishments.

Program Coordination. The Autonomous Rendezvous and Docking Program will be coordinated with the following NASA activities: the new initiative mission definition studies being conducted by OEXP, the development of high capacity, flight qualified computers conducted by OAST, and the Mars Observer mission and MRSR study being conducted by OSSA. The effort will also be coordinated with planning within the Office of Space Flight (OSF).

Resources. Projected resource requirements for the Autonomous Rendezvous &

Docking Technology Project for the first phase of the program are approximately \$15 million. The resource allocation for FY 1989 will be \$1 million.

Section 3.2 *In-Space Assembly and Construction*

3.2.1 Technology Requirements

Future space missions to exploit low Earth orbit, build an outpost on the Moon, or land on Mars will all likely involve large space structures that cannot be placed in orbit by a single launch vehicle. The most notable planned structure at the present time is Space Station *Freedom*, which will be fully assembled in space. It will be the first large permanent base placed in orbit and may also serve as a base for assembling and servicing other large structures, including Earth-observing free-flyer platforms, proposed large scientific instruments such as a lightweight 20-meter submillimeter wavelength telescope, and other large vehicles.

A lunar outpost is likely to utilize a large transfer vehicle to transport material between the Moon and low Earth orbit (LEO), and a piloted Mars mission will require a very large vehicle on the order of 1000 tons. Both vehicles will also likely use large, bulky aerobrakes up to 100 feet across (possibly larger) and will be built, outfitted (e.g., the installation of utilities) and serviced at Space Station *Freedom* or at a nearby 'garage.' Any such vehicle would also be intended for extensive reuse, and thus need to be refurbished or repaired on-orbit. Unlike Space Station *Freedom*, which will be largely built by hand, technology must be developed to enable the

on-orbit assembly and construction of these systems. Also, design methodology established to enable large space structures to be 'designed-for-construction.'

High-load carrying mechanisms could be used to simplify the design and assembly of heavily loaded, modular vehicles that use aerobraking, replaceable fuel tanks or engines. These mechanisms could absorb heavy vibrational loads from rocket motors and construct more lightly loaded, but massive, orbiting structures (such as a fuel depot) by requiring only a few attachment points. Advanced mechanisms could also enable the development of very large or heavily loaded deployable structures and simplify installation of utilities. Large area welding/bonding would enable construction of elements such as large habitats and work spaces, fuel tanks, aerobrakes, and strong, lightweight, permanent joints between structural members.

Precise telerobotic manipulation and control of large structural components is needed to bring them together for mechanical joining and to hold them accurately in place for processing a permanent joint. This must be done within a physical framework designed to facilitate space construction. Furthermore, by coupling general assembly and construction methods with telerobotic methods, large complicated structures could be built, operated, and maintained with minimal extravehicular activity (EVA) to reduce cost and enhance safety.

3.2.2 Technology Assessment

Currently, the capability to build structures of any kind in space is very primitive. Our experience is limited to a few simple experiments. Recently, two truss structures were hand assembled from the shuttle bay during STS-51B¹. During the first

1. Nov. 29 - Dec. 3, 1985

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experiment, a 13.7-meter, 10-bay truss beam was constructed from 93 (1.4-meter and 2.0-meter) struts. The value of this experiment was to test the feasibility of erecting the primary truss for Space Station *Freedom*. The second experiment involved repeated assembly and disassembly of a single bay of a larger more bulky truss structure. Neither of these experiments addressed permanent joining, and all structural elements were very light and easily controlled by hand manipulation.

We have no operational experience in permanently joining (e.g. welding or bonding) structures in space. The few Skylab experiments that were performed did demonstrate feasibility, but they did not alleviate concerns that gravity influences the convective processes in the weld bead. The Soviets have used electron beam welding to build a truss in space. However, the quality of construction is not known. Bonding methods compatible with a space environment have been proposed for Space Station *Freedom*, but these are for relatively lightly loaded applications, such as repairing a hole in a Space Station *Freedom* module.

Masses have been manipulated at the end of the shuttle remote manipulator system (RMS). All instances involved satellites weighing much less than the shuttle, which provided a comparatively stable base, and required extensive ground simulation in advance. At no time were two masses brought together and held precisely in place, as will be required to build a large space structure. We have precisely manipulated large masses and joined them during docking maneuvers, but such operations are not practical for general purpose construction methods. Currently, we can simulate manipulation in the laboratory using rigid arms but not ones with a high degree of flexibility, or with masses representative of large-scale assembly and construction operations.

Based on current programs, by 1993 our ability to build space structures will be at the level of Space Station *Freedom* technology. Large, erectable truss beams will be designed for hand and robotic assembly, but this will involve relatively small, lightweight elements. Remote manipulation will be developed to place larger objects close enough to be mated to specially designed attachments. No large planar or volumetric structures will be built, though an orbit transfer vehicle (OTV) hangar may eventually be added to Space Station *Freedom*. The Department of Defense also has projects that may involve in-space construction, but they presently rely on NASA to develop construction technology.

3.2.3 Program Description

The Pathfinder In-Space Assembly and Construction program activity will develop the basic technology required to construct large, massive structures and complex vehicles in space. One objective is to define and develop methodologies for constructing generic spacecraft components (such as aerobrakes, backbone trusses, pressurized modules, etc.) that can be applied to many different missions. This will lead to spacecraft which have assembly and construction requirements integrally incorporated into their design. The second objective is to develop the processes (welding, bonding, and mechanical attachment) required to join components in space. Accomplishing this objective will require that concepts for specialized holding fixtures and robot end effectors be developed. Methods for testing and verifying joint integrity must be developed in concert. The third objective is to develop the ability to manipulate and position large massive vehicle components precisely so that they can be permanently joined. Concepts, such as transporters, space cranes and assembly fixtures, will be

fabricated and demonstrated to achieve this objective. The fourth objective is to define the facility layout and infrastructure which is required to support constructing large spacecraft in space. A blueprint is envisioned for a facility having a high degree of construction flexibility, adaptability, autonomy, and commonality.

To accomplish this in the most general context is beyond the current capability of the program. As such, the program will be directed toward those areas which are most critical to this goal. It will not focus on designing or developing any specific structural designs (e.g. aerobrakes, transfer vehicles, scientific instruments, or large platforms), but will identify and develop common critical elements of in-space assembly and construction within these systems that require a strongly focused technical program. However, focused applications will be selected to guide the development process.

As previously discussed, the critical areas identified at this time are associated with building large structures in LEO (although this applies to structures intended to orbit Mars or the Moon as well). By focusing on the enabling technologies, and not specific systems, the program will have the flexibility to meet changing demands and will provide mission planners and systems designers with a broad range of design options. To assure that key issues are being addressed, systems studies (in cooperation with the Office of Exploration) will be conducted in parallel with technology development. These studies will focus on assessing the characteristics of large advanced space structures such as rotating systems for artificial gravity that may be critical to NASA long-range goals and objectives, and on whether the current program will enable them to be built. A key aspect of this program will be to assure that significant advances in deliverable technology are achieved.

The early part of the program will concentrate on evaluating and developing concepts (including possible hardware development) for general assembly and construction and for precise manipulation of large masses. All cases will emphasize telerobotic operation. This will lead a set of selected concepts and methods to be developed and a set of focused applications to guide the development process. An additional product of this part of the program will be design methodology tailored for space-based construction and the definition of a physical infrastructure (scaffolding, cranes, transporters, etc.) to support construction operations.

The latter part of the program (after the first five years) will integrate methods for construction and manipulation into unified robotic construction methods. It will also place more emphasis on operational autonomy, efficiency, and reliability (quality assurance). This process will also require methods by which this technology can be, in principle, validated on Earth without extensive space experiments. During this development phase, a space experiment may be conducted, if required, though one is not currently being planned.

Deliverables

PHASE I. By the early 1990s, methods for producing high-load carrying mechanical joints/mechanisms and strong permanent joints (e.g. welded/bonded) will be developed for general large-scale construction and demonstrated to be compatible with telerobotic operations. A concept to manipulate large masses telerobotically and precisely using a space crane (nonrigid) will be developed. This will be done in a testbed environment using a selected focus as a means for general development and validation. Also, advanced design-for-construction methods

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will be established and a comprehensive space-based construction system (e.g. support frames, manipulators, etc.) will be defined. This will allow mission planners broad options to develop concepts for a permanent space infrastructure of stations, platforms and vehicles with a high degree of confidence that their proposed structures can be efficiently built and serviced.

PHASE II. By the late 1990s, basic methods for joining/bonding and precise manipulation will be integrated to develop general purpose telerobotic methods for automated assembly and construction of large space structures. This phase of the program will also utilize the results from fundamental research in robotics and sensor technology to provide local autonomy to the methods such as aligning a mechanism or following a weld line. Laboratory hardware will be developed along with operational procedures to validate all selected assembly and construction concepts. A part of this process will be the development of ground-based test methods to simulate in-space operations. A flight experiment may be conducted during this phase of development.

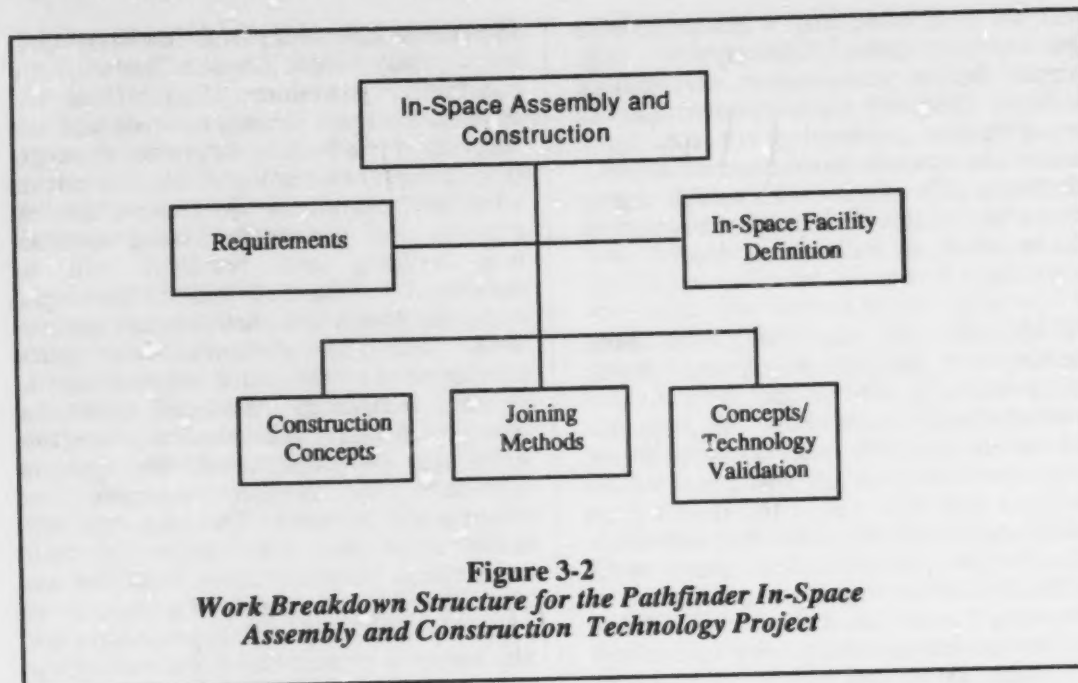
3.2.4 Organization and Management

Work Breakdown Structure. The subprogram work breakdown structure will consist of five main tasks. The first will define basic requirements for in-space assembly and construction. Factors such as size, shape, loading, and reuse will be used to identify basic structural elements (e.g. tension and compression members, permanent and temporary joints, utilities, etc.) and commonality among different systems (e.g. aerobrakes, pressurized habitats, large fuel tanks, etc.). The second task will focus on construction concepts, including methods for precise manipulation and control of large components, specialized

telerobotic operations and hardware concepts, and overall in-space assembly and construction procedures. The third task will develop the basic joining methods and any specialized supporting hardware concepts (e.g. sensors, mechanisms, etc.) to enable telerobotic operations. Mechanical joining methods and permanent joining methods (e.g. welding and bonding) will be developed. A testbed will be developed under the fourth task, and focused applications will be performed to guide development of integrated methods and to validate technology developed under the other three tasks. Advanced test methods will also be developed for ground-simulation of in-space assembly and construction methods. The fifth task will define an in-space construction system to enable large-scale operations. This task will also develop computer simulations of assembly and construction procedures and any required ground-based test methods to approximate in-space operations.

Figure 3-2 provides a preliminary work breakdown structure for the program.

Management Structure. The overall program will be managed by a program manager assigned from the OAST Materials and Structures Division (RM), with a technical advisor for telerobotics designated from the OAST Information Sciences and Human Factors Division (RC). During the initial planning phase, an advisory committee will be formed consisting of selected technical specialists from field centers, RM, RC, the OAST Space Directorate (RS) and a mission representative from the Office of Exploration (Z). The committee will be chaired by RM and remain in place for the duration of the program, with membership adjusted as required. (Once the program is in place, members outside NASA may be added.) This committee will be charged with evaluating the technical goals, objectives, and progress of the pro-



gram, and will recommend changes if deemed necessary.

The lead center for this subprogram of Pathfinder will be LaRC. This center will have responsibility for leading the development of the program plan and for the administration of the plan throughout the program. A program coordinator at LaRC will be assigned for this purpose. JSC and MSFC are currently designated as primary participating centers for program development and implementation. They will be responsible to the program manager in RM for all areas involving resources and program responsibility. They will be responsible to the lead center in administrative matters pertaining to reporting, scheduling, and milestones.

A detailed 5-year program plan (with less detailed extensions to ten years) has been developed. This planning effort was accomplished cooperatively among the

participating NASA centers and OAST. The lead center will be responsible for coordinating this activity and producing the final document. The authority to resolve conflicts will reside with the OAST program manager. This document will exclusively determine program content, center responsibilities, resource allocation, and milestones. The program will be formally reviewed each year. During these reviews, there will be opportunity for other centers to participate in the program in particular areas of expertise. As such, the program plan will be modified as required and will be extended to cover the next five years.

Program Coordination. The In-Space Assembly and Construction Technology Project of Pathfinder will be coordinated with the ongoing robotics programs in the CSTI Program, the R&T Base, and for Space Station *Freedom*. An objective of

this subprogram is to benefit from these activities, not to compete with them or to duplicate their efforts.

Coordination will also be maintained with programs to develop advanced structural concepts within the Materials and Structures Division of OAST. These activities often focus on concepts for specific classes of systems which can benefit from Pathfinder technology and which, in turn, can provide greater insight into the nature of advanced space structures.

An important activity within NASA is the planning and advocacy of long range missions and technology efforts to support those missions. As such, close cooperation will be maintained with the Office of Exploration (and to the extent required the Office of Space Science and Applications).

Overall coordination with the other subprograms of Pathfinder, the OAST space program in general, and overall NASA space plans and policy will be maintained through the OAST Directorate for Space. In particular, the Out-Reach space experiments program has accepted proposals to define three space welding experiments. If later accepted for development they would be candidates for shuttle flight experiments. As such, they would provide strong support to this subprogram of Pathfinder and will be considered during program planning.

Resources. Project resource requirements for the first phase of the program are approximately \$30 million. The resource allocation for FY 1989 is \$1 million.

Section 3.3

Cryogenic Fluid Depot

3.3.1 Technology Requirements

Current planning for future U.S. missions includes spacecraft that will be launched into low Earth orbit (LEO) with limited, or no, operationally-required cryogenic fluids onboard (for example, fuels such as liquid hydrogen and liquid oxygen, or coolants such as liquid nitrogen). Such a launch scenario may be preferred for a variety of reasons; these include launched mass reduction, thermal performance optimization, and risk reduction. Cryogenic fluids for these spacecraft will be transported to orbit separately, and then transferred to the user-spacecraft on-orbit for operations. Periodic resupply of cryogens may also be required in order to extend the useful life of this class of spacecraft, or of selected payloads accommodated on Space Station *Freedom*.

A variety of future U.S. space missions and operations will depend upon the availability of on-orbit cryogen supplies. The viability of a space-based Space Transfer Vehicle (STV), for example, will require on-orbit cryogen resupply. Also, nearer-term robotic solar system exploration missions, such as a planned Mars rover and sample return mission, could be substantially enhanced by the capability to "top-off" upper stages in LEO.

Piloted missions to Mars will (under currently feasible scenarios) be impossible without propellant supplies at an on-orbit Cryogenic Fluid Depot. Piloted Mars mission scenarios currently under study will require on-orbit assembly of the piloted spacecraft from separately launched mission elements. The total mass of such a vehicle in LEO could exceed one million pounds, 75% of which would be for

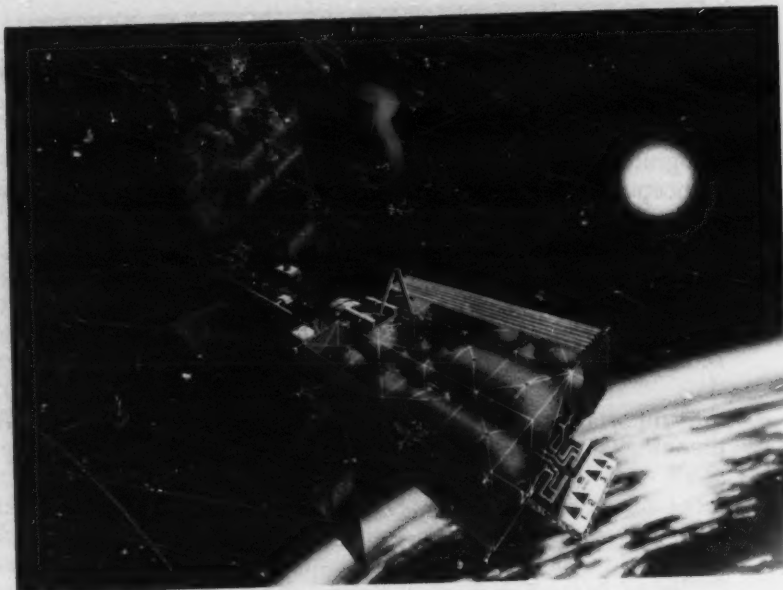
cryogenics. (The primary cryogenics for this application would be propellants, with possible additional cryogenics for life support and/or instrument cooling.) In addition, this mission would require cryogen storage for over two years to fuel return-transit staging from Mars orbit.

In order to provide a Cryogenic Fluid Depot capability, techniques for the long term storage of cryogenics in LEO and elsewhere will be required. Transfer of cryogenic fluids from storage to user-spacecraft in a microgravity environment will also be required. In addition, a variety of supporting services technologies such as robotics for spacecraft manipulation during refueling will be required.

3.3.2 Technology Assessment

Three systems currently exist for managing cryogenic fluids in a space environment: 1) small-scale storage and supply systems for superfluid helium; 2) small-scale supercritical fluid supply systems for hydrogen and oxygen; and 3) large-scale vehicle cryogen propulsion systems. None of these systems currently meet critical requirements for long term storage, supply and transfer of liquid hydrogen and liquid oxygen, nor do they meet the requirements of vehicle, tankage, and facility operations in a microgravity space environment.

Current technology programs are focused on developing a large-scale, space-based system to meet these requirements. Analytical models are under development, test facilities are being upgraded, and



Conceptual illustration of a cryogenic fluid depot in low Earth orbit

contracting efforts to perform in-space experiments are being planned.

3.3.2 Program Description

The goal of the Pathfinder On-Orbit Cryogenic Fluid Depot Program is to develop the technology base required to perform storage, supply, and transfer of subcritical cryogenic liquids in a microgravity space environment. The long term goal of this technology program is to enable on-orbit fueling and/or cryogen resupply operations for future spacecraft and space transportation vehicles, and to provide the technology for very long term storage of cryogenic fluids in space.

Program objectives include:

- (1) Development of depot conceptual designs from which critical technology areas will be identified, since the criticality of a technology depends on the depot concepts assumed;

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(2) Performance of critical research and advancement of technology readiness levels in the areas of Fluid Management and potentially in the areas of Depot Operations, Structures and Materials, Orbital Operations and Logistics, and Safety. This will include large-scale ground testing and/or analytical modeling of all critical technology items considered to be enabling to the operations of a Depot; and

(3) In-Space requirements for flight testing will be defined, even though flight experiment development is not within the scope of this program.

Initial studies will be performed to identify cryogenic fluid user needs and requirements and to develop on-orbit cryogenic fluid depot concepts to meet the identified requirements. From these depot concepts, technology requirements and deficiencies will be identified. For each of the identified technology deficiencies, a technology roadmap will be prepared that defines the criticality of the identified technology, and assesses the current state of technology readiness and the state of technology readiness required for the development of an operational on-orbit cryogenic fluid depot. Additionally, it will identify generic technology efforts in other program areas and assess the value of that work in providing the technology readiness levels required. These roadmaps will be used to lay out a time-phase technology program in each area.

Cryogenic fluid management technologies are inherent in all potential on-orbit cryogenic fluid depot concepts. A detailed technology roadmap and program was developed under the R&T Base Program in FY 88. The program includes analytical modeling, ground-based experimentation and flight experimentation. Flight experimentation requirements are being defined and are required for technology development even

though the funding requirements for the experiments exceed the current projected funding levels for the On-Orbit Cryogenic Fluid Depot subprogram in Project Pathfinder.

Cryogenic fluid managements technologies have also been identified as the most critical area for development to enable an on-orbit cryogenic fluid depot. On the basis of that assessment, the overall Cryogenic Fluid Depot program emphasizes that area in the near term. Once mission studies, user needs and requirements, and depot concepts are developed, it is conceivable that additional critical technologies may be developed.

In order to evaluate the interaction of various depot subsystems and components, a ground-based (1-g), subscale depot demonstration is required. If budget permits, this demonstration may include but not be limited to thick insulation materials, para-to-orto conversion, light weight tankage, multiple vapor-cooled shield, a thermodynamic vent system, a fluid mixer, and possibly refrigeration and/or liquefaction. A ground-based demonstration will also serve as a ground testbed for gauging and leak detection instrumentation.

The program will be implemented in two phases. The first phase will validate the fluid management ground technology and will establish depot concepts consistent with agency mission planners. The second phase will validate subscale depot subsystems and component interactions in a ground-based demonstration.

Deliverables

PHASE I. By the early-to-mid 1990s, concept formulation for a full-scale depot will have been completed. Analytical models describing all aspects of low gravity cryogenic fluid management (including storage, supply, and transfer) will be devel-

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oped and validated as much as possible with normal gravity testing. Ground-based testing of instrumentation components will be largely completed. A depot technology roadmap will be completed, assessing the current state of technology readiness and the state of technology readiness required for the development of an operational On-Orbit Cryogenic Fluid Depot. This roadmap will be used to define a time-phased technology program in each area.

PHASE II. By the late 1990s, ground-based (low gravity) validation of subsystems and integrated cryogenic fluid management analytical models will be completed. The ground-based subscale depot demonstration will be in progress. (Note: If approved separately, a cryogenic fluid management experiment may be implemented by the late 1990s.)

3.3.4 Organization and Management

Work Breakdown Structure. Figure 3-3 provides the top level work breakdown structure for the program. This structure may be revised and refined until the program is established in sufficient depth. This program is organized primarily along technology needs.

Management Structure. The overall program will be managed by a program manager in the OAST Propulsion, Power and Energy Division (RP). Technology project management responsibility will reside at LeRC in the Cryogenic Fluid Technology Office (CFTO). The program manager will have the responsibility of coordinating with other programs and Pathfinder subprograms to avoid duplication of efforts and to ensure that all technologies are being adequately addressed. The technology project manager will have the responsibility within the program of ensuring that specific technology

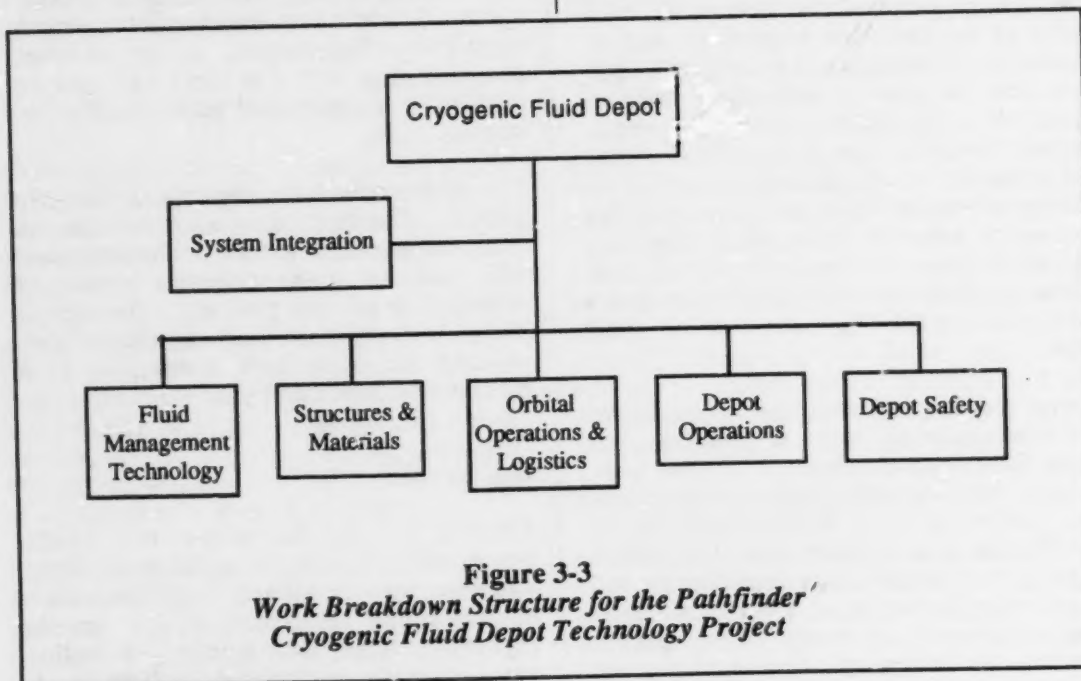


Figure 3-3
*Work Breakdown Structure for the Pathfinder
Cryogenic Fluid Depot Technology Project*

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efforts are coordinated through matrixed responsibilities in each technology discipline. The technology project manager will utilize discipline branches within the LeRC Cryogenic Fluid Technology Office as well as the expertise available in the LeRC Advanced Space Analysis Office (ASAO), JPL, JSC, and other NASA centers as appropriate. Figure 3-3 depicts the current management structure for the On-Orbit Cryogenic Fluid Depot Program. As additional technology needs become apparent, additional NASA centers may become involved.

LeRC will have the responsibility for leading the development of a technology project plan and for the administration of the plan through the program. All participating centers will be responsible to the project manager for all questions including resources, program responsibilities, and administrative matters pertaining to reporting, scheduling and milestones.

Program Coordination. The On-Orbit Cryogenic Fluid Depot Program of Pathfinder will be closely coordinated with appropriate personnel in OSF. Within OAST, coordination will be maintained with the ongoing CSTI programs in the area of automation and robotics in OAST/RC, with OAST/RM in the area of materials and structures, and with OAST/RX in the area of flight experimentation. In addition to mission analyses and requirements definition within the program, this effort will also be coordinated with the missions studies activities of OEXP, OSSA, OSO, and OSS. As appropriate, mission enhancements through technology applications will be recommended to those offices.

A systematic approach to the technology issues of a space-based fluid depot will begin with the definition of the system requirements. These requirements will be generated by considering the missions which will require depot support. These requirements

will be collected from the user organizations (Codes C, E, M, S, and Z) and catalogued in a database. Depot conceptual designs that satisfy these requirements will be generated; from these, critical technology areas will be identified. Coordination in these efforts will ensure consistency of these depot concepts with current agency planning.

Resources. Projected resources to meet the goals and objectives of the Cryogenic Fluid Depot Technology Program for the first phase of the program are approximately \$25 million. The resource allocation for the project for FY 1989 will be \$3 million.

Section 3.4 *Space Nuclear Power*

3.4.1 Technology Requirements

NASA planning for future solar system exploration includes a variety of missions which could either be enabled or substantially enhanced by the availability of high-levels of electrical power. These include both piloted and robotic solar system exploration missions, such as outer planet spacecraft and planetary surface applications. The continuing or periodic unavailability of solar radiation, or the requirements for very high power levels, make photovoltaic or solar dynamic power systems in combination with chemical power storage technologies unfeasible as the long term primary power source for the mission. Space nuclear power can meet the power requirements of these missions.

An initial outpost on the Moon (or Mars) will require approximately 100-kW of continuous electrical power for operations;

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these include life support, science, in situ resource processing research, and general outpost installation power needs. As initial outposts evolve toward permanently inhabited bases, their power requirements will grow to megawatt levels, supporting surface mining, in situ oxygen production (for propellant and life support utilization), closed-loop life support systems, and substantially augmented science operations.

Space nuclear power systems - applied to a Lunar outpost, for example - can result in LEO mass savings of hundreds of tons. For a permanently inhabited Lunar outpost, the savings can be on the order of thousands of tons in LEO.

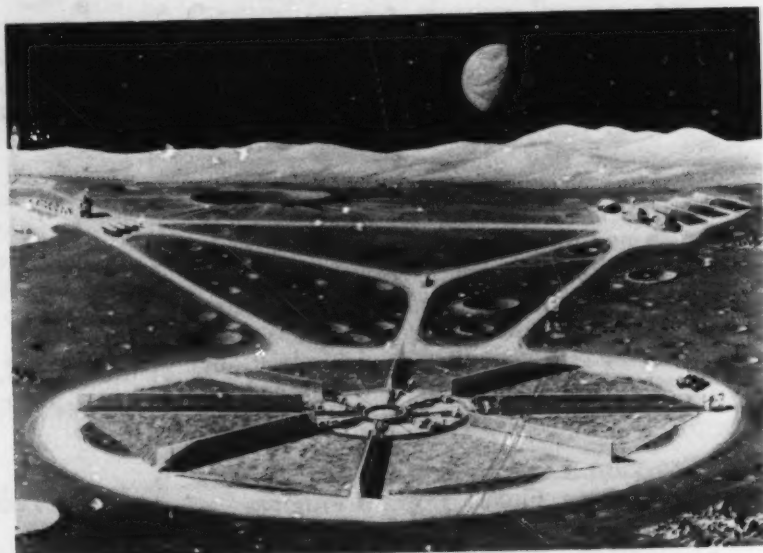
Similarly, a piloted "sprint" mission to Mars could benefit substantially from the application of space nuclear power. Utilized as the high power source for electric propulsion of a cargo vehicle for a mission, space nuclear power can result in a mass savings in LEO equivalent to approximately 3-5 heavy lift launch vehicles (HLLVs), versus a comparable cargo vehicle utilizing chemical propulsion and aerocapture at Mars. Similar savings in LEO mass requirements and in reduced time spent in transit would result from the successful application of space nuclear power to electric propulsion for robotic missions to the outer planets.

Future power requirements growth may also be needed to support nonplanetary missions. These might include support for low Earth orbit (LEO) activities such as materials processing, in-space manufacturing, and civil air and ocean traffic control systems. (The latter might operate in the high radia-

tion belts.) These missions would benefit substantially from the availability of reliable, long-life space nuclear power systems.

3.4.2 Technology Assessment

The SP-100 Program is the only space reac-



Conceptual illustration of a space nuclear power system providing power to an advanced Lunar outpost

tor development program in the United States today. A much earlier effort, the SNAP-10A system, represented this country's first and only pre-SP-100 space nuclear reactor system. The SNAP-10A provided about 600 watts of electrical power, with a system efficiency of about 1 1/2 % in April 1965. The thermal reactor operating temperature was of the order of 980°K with a system design life of one year. SNAP-10A technology is inadequate, both in lifetime and power level, to support projected long-duration Lunar surface operations or other solar system exploration missions.

Terrestrially, liquid metal reactors have

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been operated at 600 to 750°K. Current power conversion technology, represented by thermoelectric static conversion using silicon-germanium materials, provides approximately 4 1/2% conversion efficiency for the temperature gradient of interest.

3.4.3 Program Description

The Pathfinder Space Nuclear Power (SP-100) Program represents NASA's participation in the ongoing "SP-100 Ground Engineering System (GES) Project" being managed by the Department of Energy.² The objective of the SP-100 effort is to develop and validate the technology for space nuclear reactor power systems that can produce as much as hundreds of kilowatts of electric power and be capable of seven years of operational life at full power.

The GES Project's objectives will be accomplished through selected components' technology development and by validating the performance of the system through a Nuclear Assembly Test (NAT), and an Integrated Assembly Test (IAT).

The objective of the NAT is to test a full-scale reactor, as well as the instrumentation and control for the operation of the reactor, and the radiation shield in a simulated space environment. The objective of the IAT is to test a modular segment of the power conversion and radiator subsystem with an electrically heated reactor simulator.

Lifetime and long term performance of the system will be modeled, and validated through extensive component testing.

The SP-100 GES effort needs to advance space nuclear power system technology in several key areas. These include high temperature (1350°K) refractory alloys, high temperature control devices for reactor operations, thermoelectric electromagnetic pumps, high efficiency thermoelectric converters, lightweight heat pipe radiators, and power conditioning and control. Safety assessment and design and/or operational considerations are a major aspect of the GES program. The safe operation of the reactor must be assured for both normal and off-normal situations, on the ground, at launch, during operations, and during post-operations/end-of-life disposal.

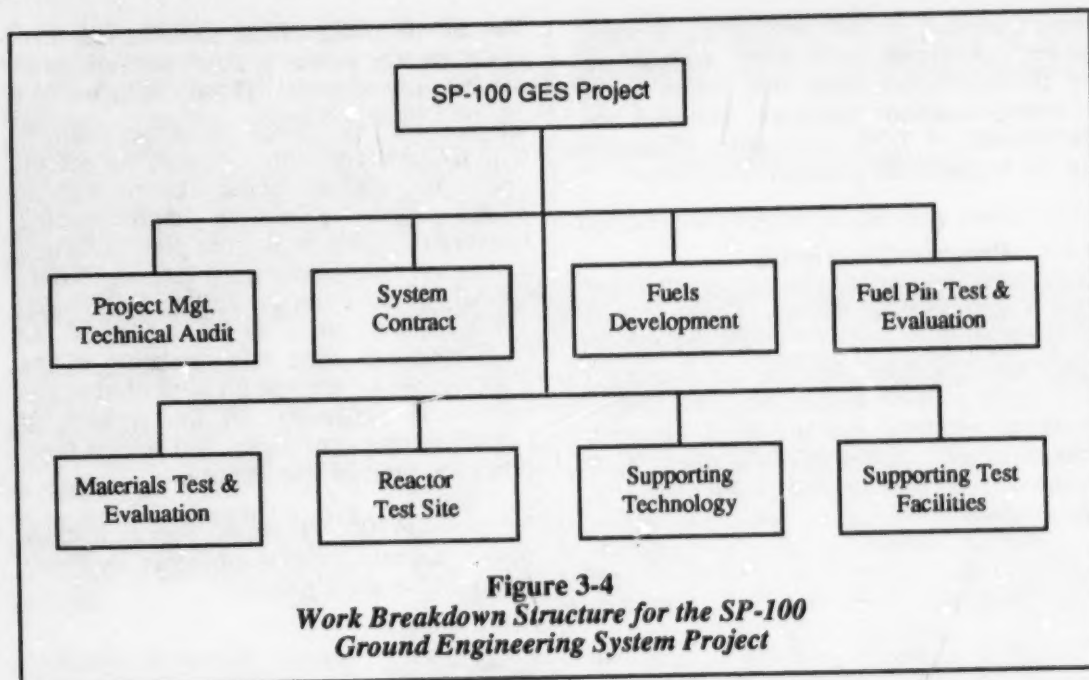
In the SP-100 Program, space nuclear power technology developments are being conducted in three phases.

Deliverables

PHASE I. The first phase of the SP-100 program was initiated in 1983 with a survey of potential civilian and military applications of space nuclear power. Based on projected applications, system requirements for the GES were defined and multiple contracts were issued to conduct assessments of several concepts and technologies that could meet those systems requirements. Phase I was completed in September 1985. A reactor and conversion systems were selected, and a power level was recommended.

PHASE II. In 1985, Phase II proceeded with the decision to implement the GES Project. In this phase, a reference flight system is being designed at the 100 kWe electrical power level, and the requirements of the GES on subsystems and components are to be defined. System performance is to be demonstrated separately through a Nuclear Assembly Test (NAT) and an Integrated Assembly Test (IAT).

2. *Note: The SP-100 GES Project is a joint effort of the Department of Energy (DoE), the Department of Defense (DoD), and NASA.



System lifetime will be demonstrated through component-level testing; life models will be developed. System reliability, survivability, scalability, and safety will be demonstrated through testing and analysis at the system level. A reference flight system design for Phase II has been defined.

Following Phase II, a flight demonstration (Phase III) of an SP-100 system is being considered. Planning is currently underway for this phase.

3.4.4 Organization and Management

The SP-100 Space Nuclear Power Program is an ongoing DoE/DoD/NASA effort and is under the cognizance of an Interagency Steering Committee established by a memorandum of agreement (MOA) between DoD, DoE, and NASA. NASA's contribution is transferred in a single block to DoE for sponsorship of the effort.

Work Breakdown Structure. Figure 3-4 provides a work breakdown structure for the program. The program is organized along discipline lines, with a systems contractor who has responsibility for integration of all activities. JPL is responsible for overall GES project management with General Electric (GE) serving as system contractor. Los Alamos National Laboratory (LANL) has project management responsibilities for nuclear systems.

An interface control board is formed for each activity outside the system contract with members from GE, the project office, and the individuals responsible for the activity. The function of the board is to ensure that the various activities are in phase with overall project flow and consistent with the tasks of the system contractor.

Management Structure. Overall program coordination will be directed by a Program

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Manager in RP. Management of the SP-100 GES Project is through the organization established by DoE.³

Program Coordination. The SP-100 GES Project involves three government agencies: DoE, DoD, and NASA. The SP-100 GES Project involves several DoE laboratories, including: LANL, Oak Ridge National Laboratory (ORNL), Hanford Engineering Development Laboratory (HEDL), and also involves two NASA field centers: JPL and LeRC.

Within OAST, the Space Nuclear Power Program is coordinated with the ongoing CSTI High Capacity Power Program. Opportunities for performance growth, reduced mass, and increased reliability and lifetimes are the key areas for consideration.

Resources. The resources allocated for the SP-100 GES technology development project are provided from the three partners in the effort, DoD, DoE, and NASA. At present, the NASA/Pathfinder share of those resources is projected at greater than \$100 million. The FY 1989 allocation is \$10 million.

Section 3.5

Resource Processing Pilot Plant

3.5.1 Technology Requirements

The use of nonterrestrial resources has the potential to provide substantial benefits to a wide variety of future activities in space by dramatically reducing the amount of material that must be launched from Earth,

and resultant high transportation costs. For example, Lunar rocks and soil could be processed into life support supplies, propellants, construction materials and shielding for general use in space, as well as on the Lunar surface. This could include resupply of LEO stations, and outfitting interplanetary missions originating from the Moon. Furthermore, any process developed for the Moon would provide the knowledge and experience required to develop similar processes in space or on other planets in a low gravity environment (such as oxygen and propellant production on Mars).

The first step in establishing the capability to produce needed materials from extra-terrestrial resources will be the validation of materials handling and processing technology during a period of Earth-dependent exploration. This will lead to increasing self-sufficiency for an array of space activities. This will be accomplished through small pilot plants. Currently, sufficient technology does not exist to select the raw materials or processes, or to design pilot plants for this purpose.

3.5.2 Technology Assessment

There is currently no established program to develop the technology to process extra-terrestrial materials. While many potential processes have been identified for the processing of Lunar and Martian materials, few have been explored in the laboratory. The feasibility of producing fiberglass and bricks from Lunar soil has been demonstrated by heating and compaction processes. To date, efforts have concentrated on the feasibility of producing oxygen and metal (iron) from Lunar soils. Currently, one company is looking at Lunar oxygen production by fluidized bed hydrogen reduction of ilmenite (an oxide of iron and titanium), and another is looking at electrochemical liberation of oxygen from Lunar simulant anorthite (a silicate of

3. See the SP-00 GES Project Management Plan for additional information.

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calcium and aluminum).

In the hydrogen reduction process, ilmenite is converted to oxygen, and titanium dioxide. A key consideration for this process is that the hydrogen required to reduce the ilmenite is recoverable. This fact is critical because hydrogen is very scarce on the Moon (approximately 75 ppm) while regolith is about 46% oxygen. While these processes and a few others are being evaluated on a laboratory scale, there are many other potential chemical processes that need to be evaluated for feasibility. In addition, there has been no significant effort on the collection and sorting of Lunar soil and rocks, or on the automation of potential processes for utilizing Lunar resources.

3.5.3 Program Description

This subprogram of Pathfinder will focus on developing the processing technology for the collection, extraction, and production of useful materials from extra-terrestrial resources. The initial emphasis will be on the production of oxygen, metals, and construction materials on the Moon. This effort will serve as the basis for a broader program to develop processing/production/manufacturing technology for a permanent, and self-sufficient Lunar settlement and for other planetary outposts. Lunar rocks and soils contain significant amounts of oxygen, metals (iron, titanium, aluminum, magnesium, silicon), and glasses which can be processed for utilization as life support supplies, propellants, construction materials, and shielding materials.

In order to capitalize on the potentials of these Lunar resources, the technology for the Lunar operations necessary to collect and sort materials on the Moon, as well as the extraction and processing methods themselves must be developed. The Resource Processing Pilot Plant program will provide the basis for the development

of large-scale autonomous processes for the utilization of Lunar resources to support permanent Lunar bases.

In the near term, the Resource Processing Pilot Plant program will focus on developing chemical/physical processes for producing oxygen, metals, and construction materials on the Lunar surface. Consideration will be given to other extra-terrestrial environments but, as a minimum, the program will be planned to meet requirements of a Lunar outpost. Within that context, the highest priority will be given to oxygen production for life support.

At the beginning of the program, several methods will be supported, leading to selection of the most promising for further development. Process evaluation criteria will include raw material requirements, power consumption, process durability (life time of production hardware), compatibility with automation, and overall synergism with other processes to reduce complexity. To guide the selection process, overall pilot plant systems studies will commence at the beginning of the program. Also, to support process development, Lunar simulants will be reproduced and methods of material collection and handling will be studied. (To the extent possible, collection and handling methods development may also be conducted, but at lower priority than process development.)

Processes to collect and sort materials robotically will also be identified and developed, but at lower priority than process development. However, it is important to consider these issues early in the program to guide the selection of candidate production processes.

Selected processes will then be developed individually in the laboratory, but with a stronger emphasis on technology development than fundamental process development. This will lead to the selection

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of a final set of methods (possibly more than one for each product) to be developed in an integrated manner. At the same time, a conceptual design for a pilot plant (or plants) will be developed. The plant concept and integrated methods development will emphasize validation of the ability to produce needed materials efficiently, reliably and in large-scale through a small pilot plant. Eventually, a laboratory pilot plant will be built to optimize and validate integrated production methodologies and hardware concepts.

Deliverables

PHASE I. By the early to mid 1990s the processes to extract oxygen, metals, and other useful materials economically from Lunar soil will be demonstrated on a laboratory scale and the candidate processes for Lunar pilot plants will be identified. Some telerobotic concepts for collecting, handling, and sorting Lunar materials will be developed. Lunar processing methodologies will be developed that have low power requirements, minimal dependence on Earth-supplied and scarce Lunar materials, and overall synergistic relationship among themselves to reduce complexity. The processes developed must also be durable.

PHASE II. By the late 1990s benchtop pilot plants compatible with autonomous operation, requiring only a minimal degree of monitoring, will be developed for the utilization of the abundant Lunar resources. They will be validated by simulating Lunar operations on artificially produced Lunar materials. Technology will be in place to begin development of actual hardware systems for a Lunar mission. Also, process scalability will have been demonstrated to satisfy the eventual requirements to have a plant on the Moon with the capability of processing large quantities of resources.

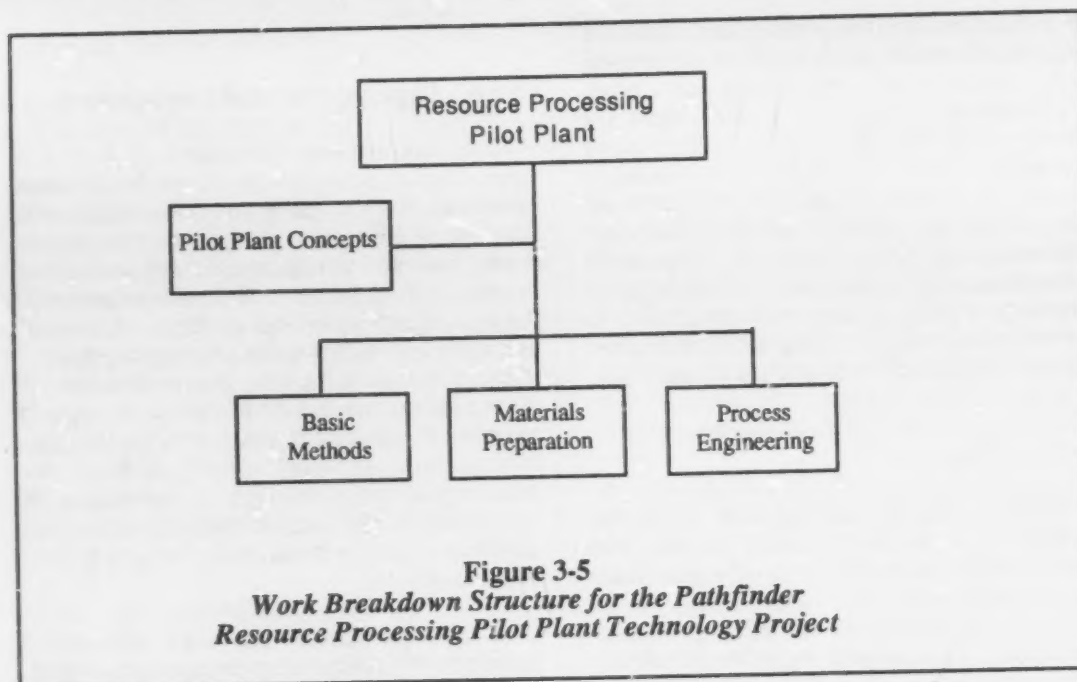
3.5.4 Organization and Management

Work Breakdown Structure. Figure 3-6 provides a preliminary work breakdown structure for the program. The WBS will consist of four main elements. The first is basic methods development. All individual methods evaluation and development will be conducted under this element. A second element will address raw materials preparation. This will include the production of Lunar simulants of raw materials to support process development and robotic collection. Also, any methods for physical or mechanical preprocessing or separating of materials would be conducted under this element (e.g. crushing, and electromagnetic separation).

The third element of the work breakdown structure will focus on process engineering. This will include mechanical systems, instrumentation, gas separation, and thermal management. Concepts for process automation and control will also be considered in this work package. Technology developed from these activities will enable the design of efficient, durable production processes at a representative pilot plant.

The fourth element will focus on pilot plant concepts, including conceptual design (and later in the program construction of a laboratory pilot plant). This element will also address synergism with other extra-terrestrial resources (such as Martian) and develop a long range program building from the technology for a Lunar pilot plant. As such, should NASA mission priorities for resource processing shift away from the Moon, the Resource Processing Pilot Plant subprogram of Pathfinder will be in a position to focus on these requirements.

Management Structure. The overall program will be managed by a program



manager in the CAST Materials and Structures Division (RM). During the initial planning phase, a technical advisory committee will be formed, consisting of selected technical specialists from field centers, RM, the OAST Space Directorate (RS), and representatives from OSSA and OEXP. The committee will be chaired by RM and remain in place for the duration of the program, with membership adjusted as required. This committee will be charged with evaluating the technical goals, objectives and progress of the program as related to an established program plan. After a program plan has been developed and approved within NASA, membership may be expanded outside of NASA.

The lead center for development of a detailed program plan is JSC. This center will have responsibility for leading the development of a program planned for administration of the plan throughout the program. A program coordinator will be

assigned at JSC for that purpose. The key participating center identified at this time for program development and implementation is JPL. All eventual participating centers will be responsible to the program manager in RM for all areas involving resources and program responsibility. They will be responsible to the lead center in administrative matters pertaining to reporting, schedule, and milestones.

Program Coordination. The Resources Processing Pilot Plant subprogram of Pathfinder will be closely coordinated with OSSA and OEXP. Within OAST, coordination will be maintained with the Information Sciences and Human Factors Division (RC) in the areas of automation and robotics, and with the Space Directorate (RS) as the focal point for all Pathfinder subprograms.

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Resources. Resource requirements for the fiscal years first phase of the program are projected at approximately \$21 million.

Section 3.6

Optical Communications

3.6.1 Technology Requirements

NASA planning for future solar system exploration includes piloted and robotic missions to the Moon, Mars, and the outer planets. The success of future solar system exploration missions will depend upon a wide variety of factors. A key measure of mission success is scientific productivity. Maximizing scientific productivity for a given spacecraft can be accomplished by providing high data rate communications between the spacecraft and mission operations on Earth (or Space Station *Freedom*).

Radio frequency microwave communications technology requires, for a fixed gain, either higher frequencies or larger antennas. Current radio frequency (RF) antennas are beginning to dominate the overall structure of typical robotic spacecraft. Ambitious robotic and piloted missions not only require higher data rate performance, they also impose stricter constraints on available power, mass, and volume, for all spacecraft subsystems, including communications. In long term surface applications, ruggedness and reliability will be important requirements. Even without constraints, RF technology would be hard-pressed to provide the orders of magnitude increases in data rates required to maximize scientific productivity for the broad array of potential future missions of solar system exploration.

Optical communications technologies could reduce the size of transmitter/receiver antennas by over a factor of ten (10:1 reduction), while offering multigigabit per

second data rates in Earth orbit, multi-megabit per second data rates throughout the inner solar system, and multi-hundreds of kilobits per second performance to the outer planets.

Unique NASA technology requirements for communications systems include high data rates, very high sensitivity receivers, large multimeter receiver apertures, and/or very long distance communications. Moreover, NASA can utilize the latent potential in the transmitted beam for science as well as communications. The science requirements could be accommodated by having a laser and a telescope on the spacecraft. Experiments such as laser-scattering off ring particles, laser-induced absorption and emission properties of planetary atmospheres, and selected backscatter lidar should be possible.

NASA also uses a spacecraft's communications beam for deep space navigation. Optical communications can meet this technology requirement. Borrowing from techniques developed by the astronomy community, astrometric navigational tracking of a spacecraft from a single optical telescope should yield navigation precision two orders of magnitude better than current intercontinentally-spaced microwave very long baseline interferometry (VLBI) tracking. Other studies indicate that optical heterodyne communications will enable missions such as Starprobe, which require realtime communications while the spacecraft travels through the solar plasma.

3.6.2 Technology Assessment

At the present time, spacecraft communications are accomplished at microwave frequencies, primarily at X-, Ku-, or Ka-band. At these frequencies, the spacecraft system is dominated by the antenna, which can be up to 4-5 meters in diameter. At the

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same time, the Deep Space Network (DSN) - the receiving stations for deep space spacecraft communications - includes the world's largest steerable radio telescope arrays. Despite the tremendous DSN arrays and large spacecraft antenna sizes, however, data rates using RF frequencies can be the limiting factor in the scientific return of a mission. In the case of the Voyager mission, the maximum data rate possible was a meager 22 kilobits per second (22 kbps) at Saturn encounter.

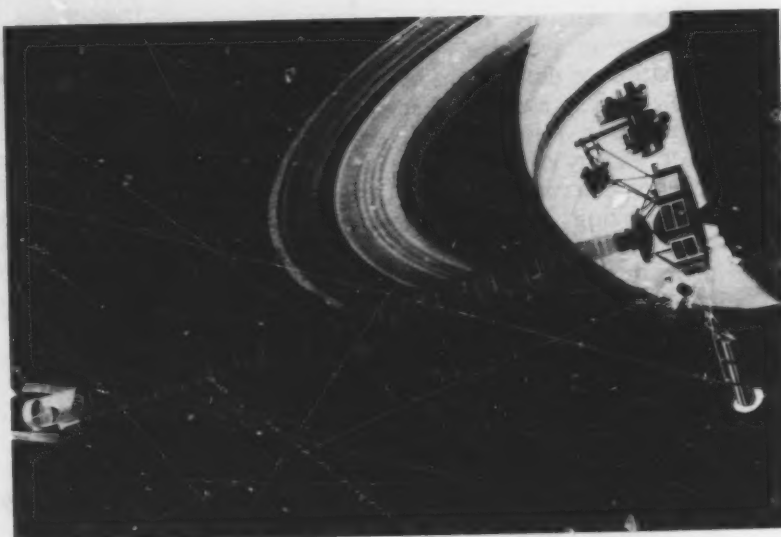
Microwave communications will have a severe impact on potential scientific return from present missions and seriously compromise even minimal future ambitious solar system exploration mission data requirements. Studies indicate that optical communications systems will communicate from deep space and near Earth distances with data rates in the 10s-100s of megabits per second (Mbps) to the 10s of gigabits per second (gbps).

Important technologies which must be developed and/or improved include diffraction-limited laser transmitters with high powers and long lifetimes, and pointing systems capable of submicroradian accuracies. All these technologies must be developed and demonstrated in space to validate readiness for operational use.

3.6.3 Program Description

The goal of the Pathfinder Optical Communications Program is to carry optical communications technology to the level of readiness required for future selection of

this technology for flight system applications in LEO, geostationary Earth orbit (GEO), and beyond. To accomplish this goal, the Pathfinder Optical Communications Program will develop the flight-qualified component and system technologies required to flight demonstrate the transfer of data at Mbps to gbps rates: (1) from GEO to LEO, (2) from GEO to GEO, and (3) from deep space to Earth and/or LEO.



An advanced robotic probe transmits high-rate scientific data back to Earth from Saturn

Critical technology objectives include the development of lightweight, highly efficient laser transmitters, high precision pointing and tracking systems, large aperture lightweight receiver telescopes, and high sensitivity direct and heterodyne detection systems.

The components will be incorporated in an engineering system and first tested in a LEO (GEO to LEO or LEO to LEO) technology demonstration. Next, optical pointing, tracking, and communication performance will be demonstrated in a

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spaceborne mission by returning data at a 20 Mbps rate from Mars to either GEO, LEO, or Earth. The latter objective may be accomplished by means of a flight experiment package onboard the Cassini mission. The data obtained from these Pathfinder technology demonstrations are prerequisite for the demonstration and selection of operational deep space and near Earth optical communications systems.

Mission analysis and requirements studies will be performed to guide technology development and the definition of planned Earth-orbiting and deep space technology flight demonstrations of optical communications. In addition, research and development of selected components will be initiated and concentrated in the areas with the highest system benefits. Operational limits of optical communications systems will be explored and expected performance will be validated.

The Pathfinder Optical Communications Program will focus on the Laser Technology Experiment Facility (LTEF) which is Space Shuttle-based, and a Cassini spacecraft-carried flight experiment package.

The program will build on technology component development performed as part of the OAST Research and Technology Base program. Component research development will concentrate on the most challenging and high-potential discipline areas in spaceborne optical communication systems. These include:

- (1) laser transmitters (semiconductor diode arrays or diode array-pumped solid state lasers with possible injection locking) with high power, high reliability, and medium to high modulation rates,
- (2) submicroradian accuracy open- and closed-loop pointing and tracking systems,

- (3) direct and heterodyne detection components for receivers, and

- (4) associated optical components such as mirrors, lenses, and filters.

A breadboard ground technology demonstration of the components in a simulated space environment will be done. Then two engineering flight demonstrations are possible during the mid to late 1990s. The first experiment could involve a laser communications link between the Pathfinder-developed LTEF and either a GEO or LEO optical communications terminal. The later flight experiment can demonstrate deep space capabilities using a Pathfinder-developed optical communications package onboard the Cassini spacecraft and either an orbital or an Earth-based receiving terminal.

3.6.4 Organization and Management

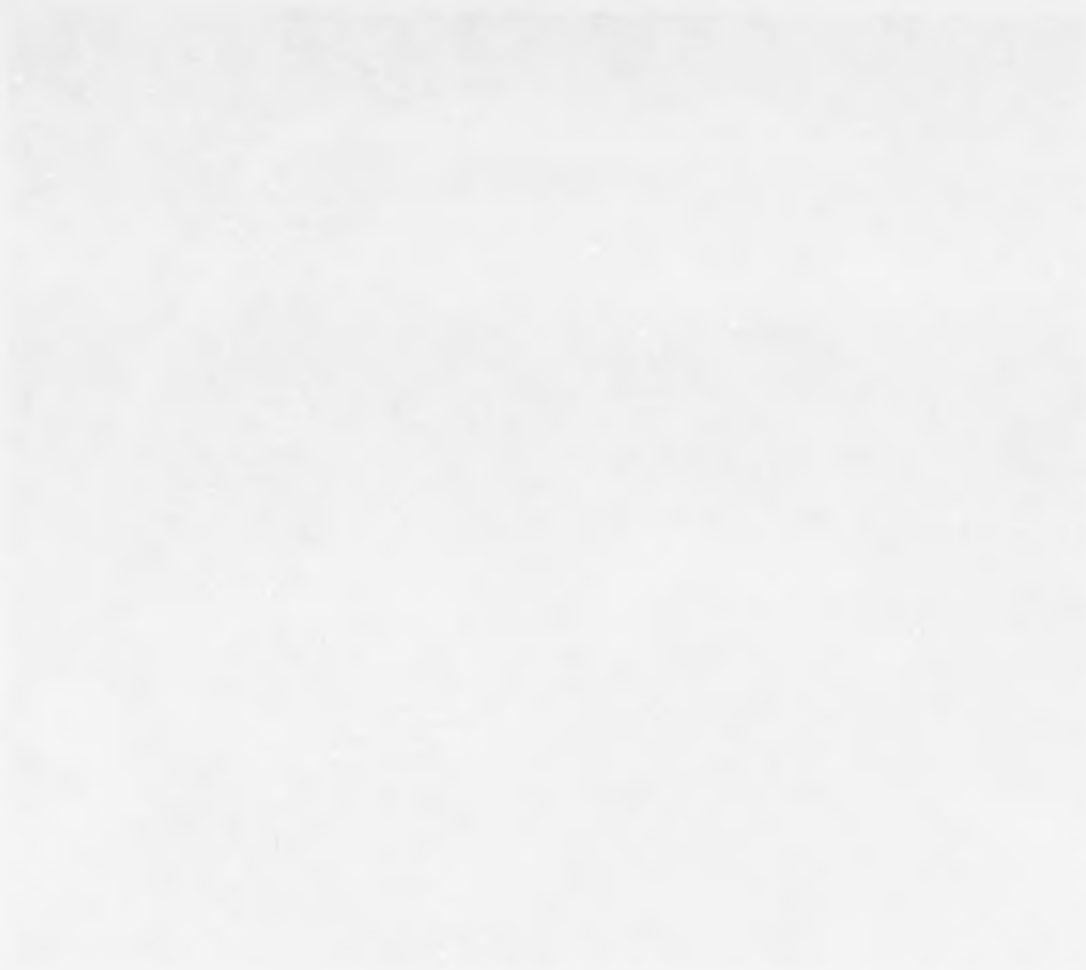
Work Breakdown Structure. The work breakdown structure for this program is still being defined. The program will be organized along discipline lines. Mission planning and flight experiments will provide near term results and a near term focus to the program.

Management Structure. The Optical Communications Program will be managed by a Program Manager in the OAST Information Sciences and Human Factors Division (RC). An Optical Communications Working Group (OCWG), chaired by the Code RC Program Manager, will help to formulate program plans and facilitate management communications. A lead center will be identified for the program, with responsibility for technical integration and reporting. Responsibility for center assignments and allocation of funds will remain with the OAST Program Manager. The OCWG will provide intramural and

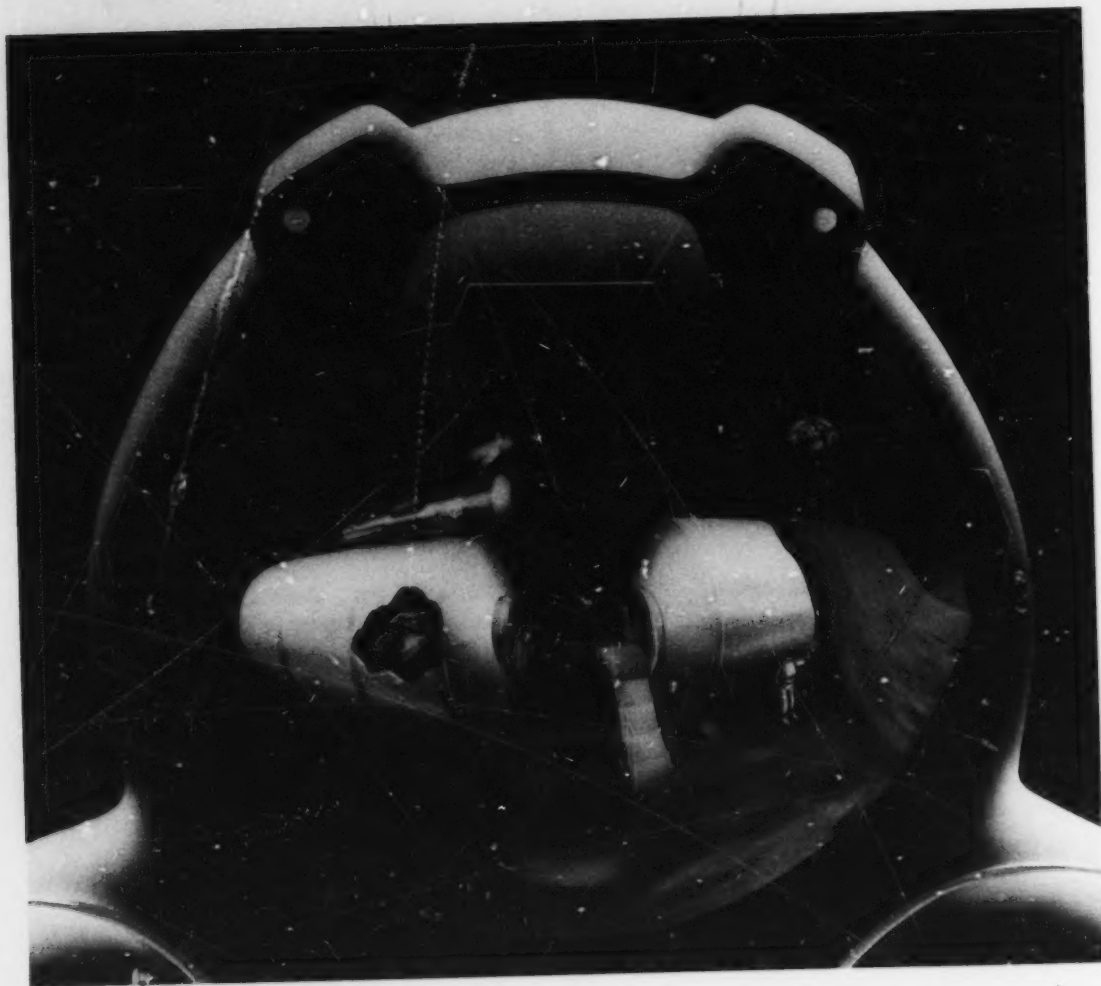
extramural coordination between NASA Centers and the federal, industrial, and university communities.

Program Coordination. The Optical Communications Program will be coordinated with the following NASA program offices: (1) the Communications and Data Systems Division (EC) and the Planetary Exploration Division (EL) of OSSA, (2) OSO (which is assessing the feasibility of optical systems for NASA's operational use), (3) OEXP (responsible for piloted exploration mission studies), and (4) OSS (as a possible carrier for the Cassini flight demonstration receiver station). Recommendations from these offices will be considered when studying or planning specific experiments and technology activities.

Resources. The Optical Communications Technology Project's anticipated resource requirements for the first phase of the program are approximately \$25 million.



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Chapter 4

Humans In Space

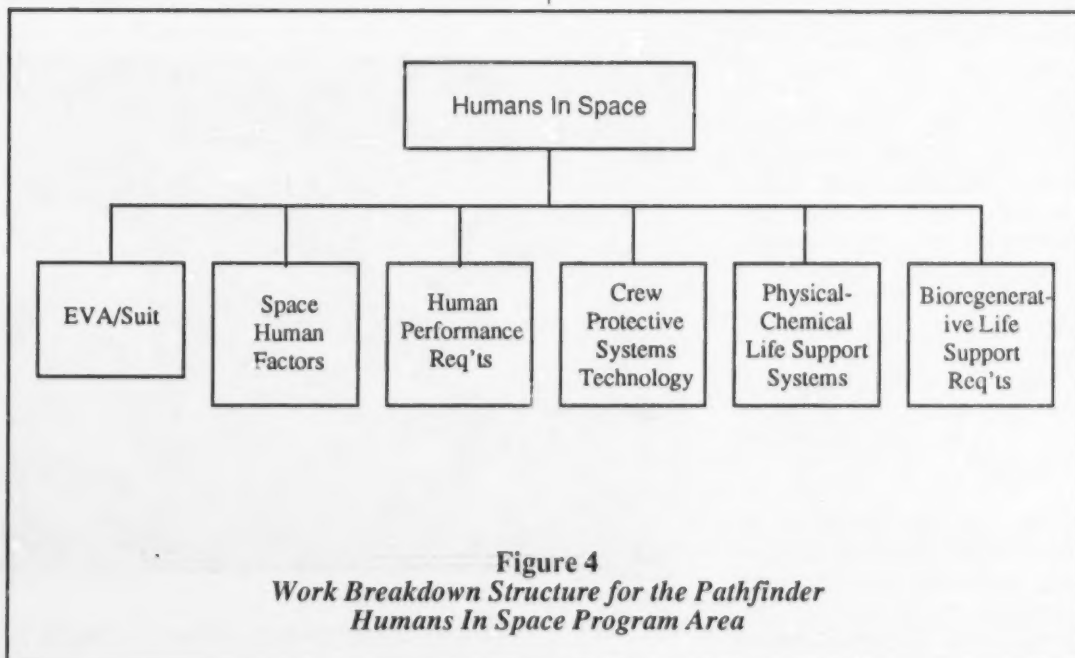
The objective of the Humans In Space program area is to conduct research to define requirements and develop technologies that will enable or significantly enhance future piloted solar system exploration. The principal focus is on two mission goals: the exploration of Mars, and the beginning of extended human operations on the Moon.

From its earliest days, research and technology to allow safe and effective human operations in space have been at the forefront of issues confronting the U.S. civil space program. Basic human health in space started out as a great unknown. Life support systems and spacesuits for extravehicular activity (EVA) were two critical challenges that faced the Mercury, Gemini, and Apollo programs. The interfaces between the as-

tronaut and the spacecraft were also problems, but because of the relatively short duration of the missions, the long term effects of space and of confinement were not impassable barriers.

During the early 1970s, the Skylab Program provided our first - and so far our only - opportunity to study longer-term issues. Also, the development of the Space Shuttle and its systems permitted significant improvements in EVA suits, life support, and crew systems; however, as was the case with the programs of the sixties, the sortie-class missions conducted by the Shuttle do not require a resolution of longer-duration mission issues.

The Space Station will create another substantial advancement of our capabilities to support humans in space, including factors related to longer-duration human flight. However, although forming a foundation upon which to build, the operational systems of the Station will not provide us with



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the capabilities we need for future, very long-duration missions to the Moon or Mars.

Pathfinder Humans In Space efforts consist of a family of closely-coordinated technology projects. These are organized in six sub-programs: (1) Extravehicular Activity (EVA)/Suit (research and technology), (2) Space Human Factors (research and technology), (3) Human Performance (requirements), (4) Crew Protective Systems Technology (research and technology), (5) Physical-Chemical Life Support (research and technology), and (6) Bioregenerative Life Support Systems (requirements).

Section 4.1 *Extravehicular Activity (EVA)/Suit*

4.1.1 Technology Requirements

Project Pathfinder is directed toward development of a technology base aimed at future exploration of the Solar System. Exploration missions include a sample return mission from Mars involving both manned and unmanned vehicles, a manned lunar base, and ultimately a manned Mars exploration of several years. The success of these missions require people to move about for a variety of activities and tasks in space and on lunar/planetary surfaces.

A reliable technology base for a high mobility, serviceable extravehicular suit, with compact, fully regenerable, portable life support systems

will be developed. Early identification of materials and design of a fully dexterous hybrid extravehicular glove are foreseen. Efficient processes for provision of breathable air and removal of waste from expired air and the onboard regeneration of the removal subsystem will also be developed. New concepts in thermal management, personal mobility concepts, and information display and control capabilities for the suited astronaut will be provided. Identification of technology needs for tools, unique end effectors, and communications will be completed.

In the longer term, such technologies will be integrated into an advanced, lightweight suit. Included therein will be servicing and cleaning techniques and a portable, compact life support system prototype. Tools, unique end effectors, and communications technologies will be demonstrated. The integrated suit and its supporting technologies will be extensively tested in ground-based facilities and prepared for flight testing.



An astronaut moves across the surface of the Moon in an advanced suit

4.1.2 Technology Assessment

At present, neither an available extraterrestrial surface space suit technology, nor life support system technology or ancillary support hardware exist. Previous Apollo experience provides a very limited data base relative to extensive lunar or Mars surface operations and explorations. Establishing this capability requires that a number of important technologies and key issues be addressed. For example, effects of long-term, unique environmental exposure conditions, and environmental parameters relevant to lunar or Mars surfaces EVAs and related hardware components have not been precisely defined.

Human performance capabilities such as locomotion and working requirements in reduced gravities of one-sixth or one-third conditions have not been simulated or evaluated. Trade-studies and experiments are needed to assess EVA man-machine requirements to establish human capabilities and limitations such as range of motion/reach envelopes, body anthropometrics, information display and controls, and metabolic profiles. The ability to identify and define EVA performance requirements, hardware design requirements, and concepts of new technologies depend to a large degree on such concentrated activities.

4.1.3 Program Description

The EVA/Suit subprogram will provide a technology base and capability for the human in space and on the lunar/planetary surface to work safely and productively outside the spacecraft or on the surface.

The objectives of the EVA/Suit subprogram are to:

1. Develop human performance require-

ments for the EVA suit, Portable Life Support System (PLSS), glove and end effectors.

2. Develop technology for suit, glove, and end effectors which provide the levels of comfort, protection, work efficiency, and mobility to meet human performance requirements.

3. Develop technology for PLSS which meets mission requirements for space and lunar/planetary EVA including mobility, regenerability, reliability, maintainability, and routine use.

4. Determine requirements and define technology options for EVA mobility systems that meet mission requirements.

5. Determine requirements and define technology options for EVA tools that meet mission requirements.

6. Develop technology for information, communications, and supervisory control interfaces that enhance safety and performance capabilities of EVA astronauts and robotic assistants.

7. Determine requirements and develop technology options for integrated logistics support of EVA and lunar/planetary base systems.

This project will provide a base of technologies which will permit NASA to make decisions about the capability of humans to perform extraterrestrial EVA activities for extended periods. Options for technology development will be provided as well. This subprogram will provide the technology for a highly mobile, lightweight, rugged pressure suit and PLSS that will allow future astronauts to explore safely and work efficiently during extended EVA activities.

Furthermore, this subprogram will provide

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for the assessment or validation of developed technologies and prototypes to demonstrate specific EVA suit and PLSS capabilities to meet human performance requirements.

The EVA/Suit program will encompass a broad array of technical disciplines at varying levels of current technology capabilities. A major focus is to provide technology for an extraterrestrial (i.e., lunar and Mars surfaces) exploration space suit assembly and glove/end effector which provide environmental protection, life support functions, and astronaut capabilities to perform useful EVA and needed scientific and/or exploratory tasks. Efforts will be directed on establishing environmental parametric requirements that meet lunar and Mars missions needs, developing trade studies to define a number of human and equipment performance requirements, and developing concept prototype hardware for testing in analog environments and demonstrations for evaluation.

Emphasis also will be directed to development of technologies for supervisory control of robotic assistants by a suited astronaut. Human performance measures will be obtained to provide insights for suit and glove design. Design aids, based on emergent technology in the existing R&T program in OAST, will be developed. Partial-gravity simulators will be used to show proof of principle, such as KC-135 flights or simulators developed for Apollo. Models of a suited astronaut will be developed from computer models now available such as the PLAID human motion simulation.

Deliverables

PHASE I. The first phase will result in definition of unique environmental, human performance, and hardware concepts for EVA suit (including Portable Life Support

Systems), gloves and end effectors resulting from investigations and trade studies. Input from mission studies prepared by Code Z will be required. Suit, glove and end effector technology previously developed by ARC and JSC will be reviewed and evaluated by a joint ARC-JSC team to determine its potential application and meet mission requirements. From this examination a decision will be made to select a single group of components for which additional research and technology development are needed to provide the technical baseline suit, gloves, and end effectors. Thus, a single suit and glove development effort is envisioned. By 1992, core technologies will be examined to the point of defining key technical issues. As a result, baseline technology concepts will be established and the equivalent of a performance specification for suit, gloves, and end effectors will be prepared. Such products will provide a technology definition for decisions about specific technology development in the second phase.

PHASE II. The second phase will result in hardware concepts and development of configurations for a prototype EVA suit and glove/end effectors. In this phase, appropriate testing and demonstrations will be performed of the components and interfaces needed to support a suited astronaut on a lunar or planetary surface.

4.1.4 Organization and Management

Work Breakdown Structure. Figure 4-1 provides a preliminary work breakdown structure for the program. The research and technology development is organized along discipline lines, with specific points of integration. There are four subelements in the EVA/Suit Technology Project: (1) Systems Studies, (2) Portable Life Support

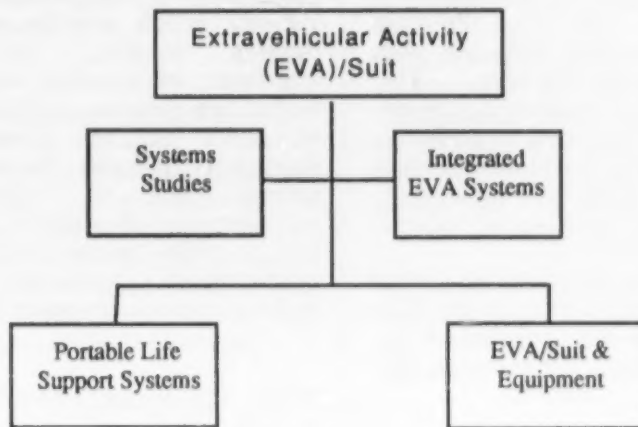


Figure 4-1
Work Breakdown Structure for the Pathfinder Extravehicular Activity (EVA)/Suit Technology Project

Systems, (3) EVA/Suit and Equipment, and (4) Integrated EVA Systems.

This structure will be revised and refined as part of the yearly updating of the Program Plan.

Management Structure. The EVA/Suit Program Manager is a designated person from the OAST Information Sciences and Human Factors Division (RC). The PLSS subelement is managed by an assistant program manager from the OAST Propulsion, Power and Energy Division (Code RP). The Program Manager and Assistant Program Manager are responsible for establishing a sound technical program, schedule, and budget, and for reporting progress.

The Ames Research Center (ARC) has been assigned lead responsibility for the Pathfinder EVA/Suit Technology Project.

An Inter-Center Working Group is established to insure the proper coordination and technology transfer among the NASA Centers participating in the research to support this subprogram. At present these are ARC, Langley Research Center, and Johnson Space Center. This Group consists of the Program Manager/Deputy Program Manager and a representative from each center who will speak and act for the center. The Working Group will be the primary means by which technical coordination is accomplished, and will be responsible for preparation and updating of the technical plan.

Program Coordination. The coordination of activities within the EVA/Suit subprogram is performed by the Program Manager/Deputy Program Manager, via the ARC-appointed Technology Project Manager and the Inter-Center Working Group. The coordination of activities

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between this subprogram and other subprograms in the Humans in Space program is performed directly by the Program Manager/Deputy Program Manager with the Pathfinder Program Manager. This program will also be coordinated with ongoing extravehicular systems activities in the Office of Space Flight, and development efforts in the Office of Space Station.

Resources. Resource requirements for the EVA/Suit technology project for the first phase of the program are projected at approximately \$28 million. The resource allocation for FY 1989 is \$1 million.

Section 4.2

Space Human Factors

4.2.1 Technology Requirements

The new exploration missions that are subjects of the Pathfinder program call for development of a technology base beyond existing state-of-the-art. Missions such as future exploration of the Moon, including an inhabited base, piloted and robotic Mars missions, and an inhabited exploration base on Mars are candidates for new technology.

Such missions will require a symbiosis of people with systems and machines to a greater and more extensive degree than in all our prior history.

A significant increase in the understanding of human performance and behavior under simulated conditions of long duration space missions will be acquired. Systematic analysis of cognitive and physical performance and cooperative behavior in such missions will serve as the basis for computer-aided design tools, enabling consistent and correct application of human

factors. Systems and technology requirements will be identified for human-rated systems which provide artificial gravity through rotation, for man-machine interfaces, information handling systems, health care systems, and habitation. Studies of small isolated group behavior in simulated mission environments will provide data and insights on human performance. A program will be defined for on-orbit experimental validation of ground-based predictions of human performance in mission environments.

4.2.2 Technology Assessment

At present, the design of spacecraft for operations and maintenance by the crew is a custom tailored procedure performed late in the development cycle. These cut and try methods require considerable iteration of mockups, 1-gravity or simulated 0-gravity rehearsals, modifications to the design and reruns time and time again. Efficient and effective human factors methods, human performance data and models of physical and cognitive activities, definition of crew needs for working on lunar/planetary surfaces and habitation are needed. Human-centered automation is necessary to obtain overall mission reliability and productivity for the few crew members working and living on lunar/planetary bases. Computer models of anthropometric features of astronauts and their physical, decision-making and judgmental activities should be extended from the current data base to lunar/planetary environments. A unified data base of the different human performance capabilities and limitations is required.

The needed technology will provide a success-oriented baseline for Pathfinder missions. Success of these missions will depend upon maximizing the unique human contributions to discovery and exploration, to the management of scientific informa-

tion, and the maintenance of the vehicle, its component systems, and the constructed lunar or planetary habitat.

4.2.3 Program Description

The Space Human Factors subprogram will enable safe and productive human performance throughout and after long duration space flight and lunar/planetary missions based on a scientific understanding and selected demonstration of human capabilities, limitations and adaptive changes.

Goals. There are five goals, each with its own subelement, in the Space Human Factors subprogram managed by OAST:

1. Space Human Factors Models and Data Base - this subelement addresses the refinement of existing computer models and databases concerning human strength and motion, perceptual and mental processes, and retrieval of the experience of astronauts to identify relevant information about human performance based on past operational experience.
2. Design tools - this subelement addresses the problem of identifying and incorporating into the design process information about human-machine compatibility in manned space systems.
3. Crew Support systems - this subelement addresses the problem of new technology interface needs of the crew in the spacecraft and in the manned lunar/planetary base. It also includes technologies from materials science and instrumentation for health monitoring which are intrinsic to human performance.
4. Human Capabilities Enhancement - this subelement addresses the definition of information display and integration for crew operations and maintenance.

5. Human-Automation-Robotic systems - this subelement addresses the problem of determining the mix and match of humans with automated or autonomous systems and robotic systems, including the allocation of functions between and among humans, automation and robotic systems.

Objectives. Objectives of the Space Human Factors subprogram, are to

1. Enable, enhance or extend the human's unique capabilities to significantly increase the benefit from long duration space missions.
2. Develop the requirements for human-machine compatibility and provide significant improvements in the capability to incorporate such requirements in manned space systems.
3. Determine the performance requirements for systems of humans, automation, and robotics and for allocating functions of humans and systems to meet these requirements.
4. Provide methods and techniques to meet human safety and performance requirements.

This subprogram will provide a base of technologies which will permit NASA to make decisions about the capability of humans to perform well in space for extended periods and make rapid readaption upon return to a gravity field.

Further, this subprogram will provide assessment or validation for the developed technologies and prototypes to demonstrate specific capabilities to meet Space Human Factors requirements.

Mission needs for lunar and planetary exploration will be used to identify Space Human Factors needs and to compare such needs with known human capabilities and

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limitations. Assumptions about Space Human Factors requirements and human tasks will be developed to supplement formal mission studies. Efforts will be directed to identifying and using the experience gained from U.S. flights of Apollo, Skylab, and the Shuttle and Soviet space missions as they relate to these new missions. The Space Human Factors program will focus on the development of techniques for modeling human physical and cognitive (i.e., decision-making, judgments, perceptual functions) activities.

These computational models of human performance will be validated against data collected in moderate fidelity simulations of mission tasks in order to demonstrate the scope, reliability, and usefulness of the models and underlying data.

To this end, the concept of an automated habitat test bed will be studied and supported, if feasible, to allow simulation and validation studies of increasing complexity and fidelity to be conducted over the course of the Pathfinder program. A major focus is development and validation of new concepts and methods for optimizing the human-automation-robotic lunar/planetary workforce. Human-automated-robotic (H-A-R) systems will be developed, as needed, to support exploratory missions and associated human performance needs. Multisensory systems for information integration in the spacecraft and in the lunar/planetary habitat will be used to develop an interactive information management system and to aid in operational planning and teleoperations. The interactive information management system will include advanced display and control technology. Test and demonstration of the emergent technologies will be performed to insure their adequacy to meet mission needs.

Deliverables

In the first part to be completed by early to mid 1990s, models of human performance will be refined and completed. Specific topics of human strength, motion, human-computer interaction, and cognitive activities will be modeled.

These will be used to define human and robotic functions and tasks. An integrated Space Human Factors data base will be available and will include lessons learned about crew performance from Apollo, Skylab, and Shuttle missions. A set of design and evaluation tools will be developed from existing methods, initially as conceptual statements of performance, to assist mission and system analysts to evaluate human capabilities and limitations in spacecraft and lunar/planetary habitats.

As the project matures, scientifically validated human performance models will be developed that identify manned-system requirements, including the environment, individual, group, and organizational requirements for safe and effective performance throughout long duration missions in space and on lunar/planetary surfaces. These models will be applied to habitat and vehicle designs using advanced computer-aided design tools. Methods and techniques will be found for analyzing and predicting complex human-machine and human-environment interactions, with long periods of group isolation and total dependence on life supporting technology. Countermeasures will be applied for performance decrements related to exposure to unnatural gravity fields and may include compensatory systems engineering, behavioral strategies, improved approaches to astronaut selection and training, and design support tools. A clear understanding of Space Human Factors, system design and technology requirements for artificial gravity systems will provide options for long duration manned missions.

By the late 1990s, the second part will provide validated Space Human Factors models which will have been applied to a technology for H-A-R system concept. These will result in detailed guidelines for crew support systems and for human-capability enhancement systems. Collection of data related to crew design considerations for deep space transit will be completed to verify early design concepts. Special emphasis will be placed on human-machine systems design guidelines, human-computer interaction criteria and information management systems to support lunar/planetary explorations.

The major deliverables and products from this subprogram managed by OAST are:

1. Tools for design of human-machine systems.
2. Techniques for defining and meeting

crew requirements (e.g., information, health, habitation, zero gravity and artificial gravity, man-machine interfaces, and so on).

3. Planning, evaluation and validation methods for human-automation-robotics systems, including function allocation schemes.

4. Techniques to enhance human capability.

5. Space Human Factors models.

4.2.4 Organization and Management

Work Breakdown Structure. The Space Human Factors program, managed by OAST, is organized to provide design tools, technologies, and supporting models and data. A preliminary work breakdown structure for the program is given in Figure

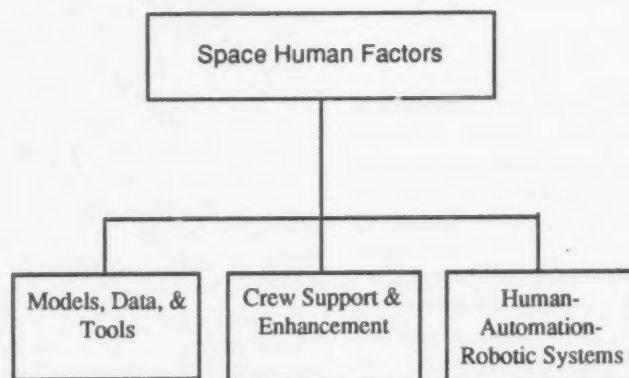


Figure 4-2
*Work Breakdown Structure for the Pathfinder
Space Human Factors Technology Project*

4-2. The research and development effort also has specific point of test, evaluation and integration. The structure will be revised and refined as part of the annual updating of the Program Plan.

Management Structure. The Space Human Factors Program in OAST is managed by the Program Manager for Human Factors in the Information Sciences and Human Factors Division (RC). Responsibility for Center assignments, approval of project plans and funding allocation will remain at Code RC. Quarterly project reports will be submitted to OAST tracking progress against Level 1 schedules and identifying any problems, issues or significant accomplishments. NASA Centers are designed to implement specific tasks.

Program advice and coordination is provided by the Space Human Factors Inter-Center Working Group, which is composed of representatives from the NASA Centers and those NASA Offices that would be potential users of the technology. OAST will sign appropriate Memoranda of Understanding (MOUs) with each office.

Program Coordination. The coordination of activities within the Space Human Factors subprogram is performed by the Program Manager/Deputy Program Manager, via the Inter-Center Working Group. The coordination of activities between this subprogram and other subprograms in the Pathfinder program is performed directly by the Program Manager/Deputy Program Manager in coordination with the Pathfinder Program Manager.

Resources. Projected resource requirements for this activity for Phase I are approximately \$29 million. The resource allocation for

FY 1989 is \$1 million.

Section 4.3 ***Human Performance***

The following sections describe the four subelements of the Human Performance ;subprogram, i.e., Artificial Gravity, Radiation, Space Human Factors, and Extravehicular Activity (EVA). The organization and management section will be considered together after the detailed descriptions of the subprograms.

4.3.1 *Artificial Gravity*

4.3.1.1 Technology Requirements

For humans raised in the 1-gravity (1-g) field of Earth, one of the most anomalous conditions of space flight is weightlessness. In its attempts to adapt to this novel environment, the body undergoes changes in the neurovestibular, cardiovascular, musculoskeletal, hormonal, and immune systems. Except for space sickness, which affects about half of all space travelers and generally lasts 2-3 days, weightlessness appears to be reasonably well tolerated over the short term. However, as time in weightlessness lengthens, it becomes increasingly important to exercise vigorously to offset the loss of muscle mass and to keep the heart active and healthy. However, calcium continues to be lost from the bones over the duration of the mission. It is believed that calcium loss of about 25% would make the bones vulnerable to breakage in weightlessness. It is also believed that a loss of this magnitude may not be recoverable after return to Earth. In order to protect astronauts from the weakening of the various bodily systems, and to relieve them of the necessity of engaging in grueling daily exercise, artificial gravity has been proposed as the candi-

date countermeasure-of-choice on long-duration missions.

4.3.1.2 Technology Assessment

At present, no human artificial gravity program exists. To date NASA has flown only relatively brief missions for which artificial gravity was not a requirements. The Soviets have flown much longer missions, but they have yet to experiment with artificial gravity as a solution to documented problems of weightless. It is generally agreed that for missions of one year or more, artificial gravity will be strictly required. What is not known is whether artificial gravity much be experienced continuously or if brief and repeated exposures would suffice. Other questions concern the specifics of the artificial gravity system needed and possible negative side effects.

Questions about artificial gravity will result in studies in the following main areas: (1) rotation rate, (2) duration, and (3) G-loading.

Rotation Rate Studies. Artificially-generated centrifugal forces can be used to replace gravitational forces. Although rotating vehicles, onboard centrifuges, external centrifuges, or tethers might be used to generate the necessary acceleration, there is no a priori assurance that, however implemented, this approach will be fully satisfactory. Because rotation provides other unwanted effects, such as angular accelerations, linear force gradients, coriolis forces, and cross-couple stimulation, in addition to the desired effect of producing artificial gravity, we must study and understand these side-effects of centrifugation in a systematic manner before committing to the use of artificial gravity for long duration missions.

Duration Studies. Although artificial gravity may be used to prevent physiological deconditioning in space, the thresholds

of G-duration in protecting and maintaining various physiological systems remain unknown and studies using both humans and animals are needed.

G-Loading Studies. When using artificial gravity to prevent physiological deconditioning in space, the threshold for G-magnitude in protecting and maintaining various physiological systems remains unknown. Experimental studies with both humans and animal models need to be conducted to specify the threshold of G-magnitude needed to protect against physiological deconditioning.

In addition, studies are need to provide information on realistic tradeoffs between G-duration and G-magnitude as applied to extended manned missions.

4.3.1.3 Program Description

The goal of this program is to provide fundamental information in support of the use of artificial gravity in long-duration manned missions. The objectives of this program elements are:

1. To specify the conditions under which neurovestibular adaptation to rotating environments can be optimized.
2. To determine the ability of individuals to adapt to transitions among various rotating and nonrotating environments.
3. To develop techniques to define and measure critical deficits that may result from the use of rotating environments to produce artificial gravity and that may adversely impact neurovestibular function and performance during long duration manned missions.
4. To develop techniques to define and measure the results of intermittent versus chronic centrifugation in preventing the de-

conditioning effects of exposure to micro-gravity.

Deliverables

Phase I. Studies to establish the preliminary rotation, duration, and loading requirements for artificial gravity will be completed during Phase I. Descriptions of the effects of intermittent centrifugation and chronic rotation will be made and determination of the strategies for use of artificial gravity will be in place.

Phase II. The direction of the artificial gravity work in Phase II will be influenced by decisions made by OEXP and commitments made at a national level, as well as by results obtained in the Phase I research. As appropriate, the results of the artificial gravity research will be timed to support the development of the Variable Gravity Research Facility (VGRF), an effort outside the current scope of the Pathfinder initiative.

4.3.2 Radiation

4.3.2.1 Technology Requirements

The crew members of a piloted mission to Mars or a Lunar base will be unavoidably exposed to ionizing radiation as they pass through the inner trapped proton belt, the outer trapped electron belt, and through the Galactic Cosmic Ray (GCR) flux of interplanetary space. Moreover, outside the Earth's magnetosphere, there is the possibility for exposure to proton radiation from Solar Particle Events (SPE). On the surfaces of the Moon or Mars, the GCR and SPE fluxes will be approximately half that of free space, because of the 2- π shielding provided by the planetary mass. In addition, there will be some shielding provided

by the thin Martian atmosphere.

4.3.2.2 Technology Assessment

The dose equivalents and radiation health risk for piloted Mars or Lunar Base missions can be estimated, but these estimates are uncertain, perhaps by a factor of 2 to 4. Shielding calculations must be refined. Particle transport through absorbing material is a complex function of the particle fluence, the charge and energy (velocity) of the particles, the interaction of the primary particulate radiation with the spacecraft materials and with crew members' bodies, the production of secondary density or Linear Energy Transfer (LET) of the primary and secondary particles in tissue, the Relative Biological Effectiveness (RBE) of different particles, and other factors.

For many of these factors listed above, the uncertainties are very large and must be reduced if NASA is to optimally fulfill its commitment to the ALARA principles, that is to maintain dose-equivalents As Low As Reasonably Achievable. For short duration (less than 90 days) Earth orbital missions, there has been no problem in meeting ALARA. For Lunar and Mars missions, the dose-equivalents could be an order of magnitude higher than those previously experienced by any astronaut. Therefore, dosimetry that is adequate for Space Shuttle missions is not adequate for Moon/Mars mission. Moreover, sudden large changes in solar particle flux may occur. And in deep space, GCR is the prime source of biologically-damaging ionizing radiation. Other technologies must be developed and evaluated to ascertain if the depth-dose-equivalent, and associated risks, can be reasonably reduced. These include active dosimetry, SPE warning systems, and so on.

4.3.2.3 Program Description

The goals of this program are to develop a needed understanding of the radiation threat to the human participant and to devise methods for protecting the space traveler from unnecessary radiation risk. Specifically, this program will:

1. Develop the technology requirements and provide the information base necessary to a) adequately measure space radiation doses received by Moon/Mars mission astronauts, b) convert the doses to dose-equivalents, c) assess the radiocarcinogenic and other risks to the individual, d) counsel the individual regarding the risks, and e) manage the risks by providing optimal shielding where reasonable, or by curtailing a career when necessary.

2. Develop requirements for countermeasures for radiation-induced biological damage from chronic GCR and potential SPEs, including optimized shielding, improved avoidance capability through improved forecasting and prediction, pharmaceutical means, and identification of less susceptible crew persons for the missions.

Deliverables

PHASE I. The first phase will include the development of improved mathematical models of the GCR environment as a function of location in space time (day/night), and solar cycle, and of GCR transport and interaction (fragmentation) with various potential spacecraft materials and human organs and tissue. Improved models for calculating organ level will be developed and new methods of radiological health risk assessment will be evaluated. Phase I will begin studies to develop improved active area dosimetry for measuring the highly mixed radiation field inside a Moon/Mars mission spacecraft or base, and to improve area dosimetry (active or passive) for meet-

ing the legal requirements of accurate records, risk counseling, exposure budgeting and risk management.

Methods for improving the techniques for forecasting and instruments for measuring SPE-generating activity on the Sun will be developed and a reexamination and improved analysis of the historic solar activity records will be made in order to estimate the largest conceivable SPE and the probability of occurrence.

PHASE II. Requirements for optimized automated onboard SPE alarm systems or forecasting instrumentation for the Mars/Moon mission spacecraft and bases will be developed. Requirements for "storm shelters" optimized for protection against potential SPE will be developed. This will involve evaluation of the capabilities of different materials, temporary body shields (e.g., pump water to a flexible cylinder around the body) and partial body shielding (e.g., torso and eyes only). Requirements for rapidly constructable contingency radiation shelters to protect an astronaut unable to return to base during an SPE (perhaps from lunar or Martian materials) will be also be developed.

4.3.3 Space Human Factors

4.3.3.1 Technology Requirements

Future space-flight missions, such as a lunar base or a Mars mission, will involve small groups of individuals living and working together for extended periods in isolated, confined and high-risk environments. These space-flight conditions promise a continuing series of new challenges to scientists and engineers in the development of advanced technologies to maintain and enhance human safety, well-being and productivity in space.

The Space Human Factors subelement will

determine technology requirements for three general areas: crew factors, (i.e., organization, interpersonal interactions, and communication), environmental factors (i.e., habitability and environmental stress); and performance factors (i.e., mission task analysis, human-machine interactions).

4.3.3.2 Technology Assessment

Information regarding human factors during actual space flight is based largely on anecdotal data. However, experience in long duration, isolated, confined and potentially dangerous environments analogous to space has shown that non-adaptive behavior can emerge. In environments such as undersea habitats, submarines, and polar stations in the Antarctic, symptoms of stress that can reduce crew effectiveness and productivity have been observed. In long duration, isolated and confined space flight conditions, the dynamics of crew interactions will also pose significant challenges.

The available empirical data on performance during microgravity and after returning to a gravity environment after prolonged microgravity exposure is limited. Evaluations of technologies proposed to offset the physical effects of microgravity must also include performance measures.

Human operations in advanced and extended duration missions will require new understanding of skill and social mix. Questions of crew size and compositions, workload and scheduling must also be examined in light of the demanding human requirements of exploration missions. At present, established principles do not exist to guide the implementation of human/automated systems. Before implementing automated technologies, we must understand the tasks to be performed and the benefits and potential errors involved in various approaches to the allocation of tasks between humans and machines, between the crew

and the ground, and the implication of the communications and other technologies required to support these decisions.

4.3.4.3 Program Description

The overall goal of the Space Human Factors area is to provide the information base that is required to enhance and maintain the safety and productivity of crews throughout and after long duration missions. This goal is based on developing a comprehensive understanding of human capabilities, design requirements, and adaptive behaviors in isolated and confined environments as associated with exposure to prolonged microgravity and space flight conditions.

Specific objectives are as follows:

1. Conduct habitability studies including volume requirements.
2. Conduct crew factors studies, to include guidelines for crew composition, compatibility, chain-of-command, and communications.
3. Conduct human/machine studies including allocation of human and automated functions.
4. Conduct mission/operational task analysis.
5. Conduct performance studies in micro- and artificial gravity.
6. Establish an analog testbed in which space human factors requirements can be assessed.

Deliverables

PHASE I. By the early 1990s the related activities will be completed and preliminary

determination of the following requirements will be in place:

Information on crew size, mix, leadership, and other characteristics.

Validated guidelines for crew organization, including group structure, chain-of-command, crew composition, and motivation.

Habitability, volume and design guidelines.

Missions Analyses

- Work/Rest Schedules
- Task Definition

Preliminary Training Requirements

Preliminary Human-Machine guidelines

- Design tools
- Guidelines for human-machine function allocation
- Error-tolerant operation interfaces
- Workstation information displays and integration for crew operations and maintenance

Preliminary Crew communications requirements

PHASE II. Phase II will be concerned with completing the human-machine guidelines definition and the crew communication requirements begun in Phase I. Phase II will also include the simulation and flight testing of facilities and protocols identified in Phase I.

4.3.4 ExtraVehicular Activity

4.3.4.1 Technology Requirements

Protecting the well-being of astronauts before, during and after extravehicular activity (EVA) is a continuing challenge of space-flight. The demands of space activities, es-

pecially construction and exploration tasks, will require an extension of the time and workload constraints that are already being envisioned for space station assembly in the 1990s. In addition, the demands of life on a planetary surface will present unique challenges to EVA planners (e.g., significant gravitational forces, dust, maintenance requirements) that may require new solutions to the EVA question.

4.3.4.2 Technology Assessment

As we move toward longer and more distant missions, the time and energy spent on preparing for, executing, and recovering from EVA will become increasingly precious. EVA solutions may include improved suit technologies, autonomous rovers, or various combinations of the two that will allow future astronauts to perform productively on exploration missions. Current pre-breathing regimes, requirements for EVA radiation protection, environmental health and workload monitoring, and emergency return strategies will be insufficient to meet the challenges of those missions.

4.3.4.3 Program Description

The goal of this subelement is to develop environmental and physiological requirements for EVA including establishment of environmental requirements, establishment of medical protocols and guidelines for medical monitoring. Performance studies will include biomechanics and activity measurements, and workload and scheduling requirements for exploration EVA.

Deliverables

PHASE I. Physiological, performance, and environmental requirements for EVA should be completed during Phase I.

PHASE II. During this program phase, mission-specific requirements for the exploration missions would be further developed, and scenario-dependent aspects analyzed.

4.3.5. Organization and Management

Work Breakdown Structure. Work in the Human Performance area is broken down into the subelements shown in figure 4.3, i.e., Artificial Gravity, Radiation, Space Human Factors, and EVA. Artificial Gravity includes rotation, duration and G-Loading studies; Radiation includes risk assessment, biological dosimetry, solar particle event studies, operational dosimetry, and countermeasure; Space Human Factors includes Crew Factors and Human Factors; EVA includes related physiological, environmental and performance requirements.

Management Structure. The Human Performance Program Manager is located in the Office of Space Sciences and Applications, Space Medicine and Biology Branch (Code EBM) NASA HQ. The Program Manager assumes overall responsibility for the direction and execution of the program and for management and coordination of the subelements. Subelement managers, also located in the Space Medicine and Biology Branch, will have specific responsibility for the direction and implementation of each subelement activity. Advice will be provided to the Program Manager by NASA's Aerospace Medical Advisory Committee and the Committee on Space Biology and Medicine on the NRC. Technical support to the program will be provided through the activities of relevant science working groups. HQ will provide the lead in the Human Performance Activity, while Ames Research Center and Johnson Space Center will play key roles in

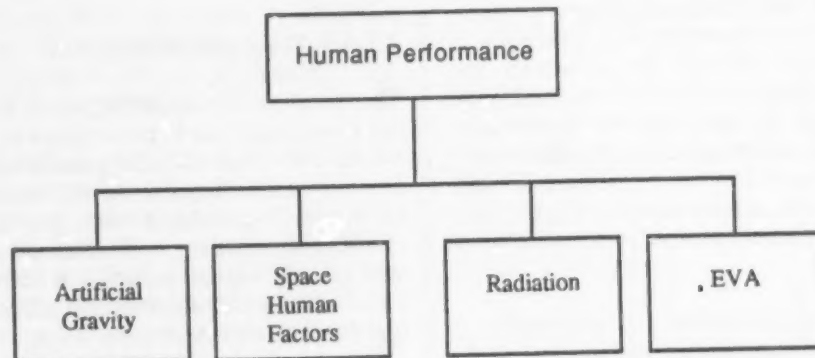


Figure 4-3
*Work Breakdown Structure for the Pathfinder
Human Performance Requirements Project*

the implementation of this program.

Program Coordination. The Human Performance Program is integrated with programs in Operational Medicine, Biomedical Research, Environmental Monitoring, Gravitational Biology, Biological Systems Research and their related flight components within the Life Sciences Division (Code EB) of OSSA. Coordination of the Human Performance Program and other subprograms of the Humans In Space thrust of Pathfinder will be through the Pathfinder Program Manager.

Resources. The Pathfinder requirements projected for the Human Performance program for its first phase are approximately \$41M. The amount allocated for FY 89 is \$2.125M.

Section 4.4

Crew Protective Systems Technology

This Pathfinder Humans In Space subprogram will focus on the research and technology needed to enable protective measures against the adverse long-term physiological effects of microgravity and in-space exposure to radiation. The subprogram will address (a) artificial gravity systems, and (b) radiation protection (including vehicle/system design strategies and materials). At the present time, this subprogram is at a relatively low level of planning maturity. It will be substantially revised in a later version of this document. The Crew Protective Systems Technology program was deferred in FY 1989.

Section 4.5

Physical-Chemical Closed-Loop Life Support

4.5.1 Technology Requirements

Mission studies are currently underway to define options for long-duration human exploration of the Solar System. Mission options include both the implementation of an evolutionary human presence on the Moon and piloted missions to Mars. In a lunar scenario, early robotic exploration would precede the creation of man-tended installations on the Moon's surface. These would then evolve into permanently inhabited bases. In a Mars scenario, robotic precursors would be followed by piloted sprint missions and the eventual implementation of a continuing human presence on the Martian surface.

The development of regenerative life support technologies will provide a high degree of closure in the crew life support system for both lunar and Mars long-duration piloted exploration missions. In addition, although not required for the effective implementation of nearer-term systems such as the Space Station, as human operations in Earth orbit continue to expand, increased closure of life support functions will reduce loading on limited Earth-to-orbit launch systems.

4.5.2 Technology Assessment

Consumables per day required to support a crew of six consist of 385 pounds of food, water, air, and lithium hydroxide (for carbon dioxide removal), which in addition to drinking water, includes water provisions for crew showers and clothes washing. The Space Shuttle-based portable life support

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system used for extravehicular activity (EVA) expends approximately 2 pounds of water, oxygen, and carbon dioxide sorbent per EVA hour. Total Space Shuttle waste from all sources approaches 200 pounds per day.

The Space Station, based upon a 90-day resupply period, may utilize a proposed air revitalization system which is largely closed, and partial water reclamation from wash water, humidity condensate, and urine. The large quantities of human wastes and trash will be transported back to Earth for disposal. Food, spares, nitrogen, and make-up oxygen and water will be resupplied to the Station on a periodic basis. Much longer duration missions in which resupply will not be frequent or practical will require significant technology improvements in life support systems.

4.5.3 Program Description

This subprogram of Pathfinder will focus on developing highly efficient air revitalization, water reclamation, waste treatment, and air and water quality technologies. These will be developed and integrated into a total life support system which will minimize the requirements for stored consumables and significantly increase or eliminate the resupply period. This technology has the potential for an order of magnitude reduction in the mass of life support expendables and associated transportation requirements.

A closed-loop life support system, exclusive of food productions, will be developed through a series of increasingly complex steps, beginning with physical and/or chemical process and development, followed by component and subsystems development, and culminating in a highly reliable and completely integrated system. As appropriate, biological subsystems will eventually be integrated with the physical-

chemical subsystems to evaluate a hybrid closed-loop life support system.

Air revitalization will address oxygen generation, carbon dioxide removal, nitrogen generation, and both trace and microbial contaminant removal. Water reclamation and solid waste treatment management will be pursued. Systems technology necessary to provide useful substances from local resources, e.g., oxygen from the Mars atmosphere, will also be pursued. Regenerable, portable life support systems and their interfaces with the primary life support system will also be developed.

Control systems utilizing artificial intelligence and expert knowledge systems will provide a high degree of reliability and safety to assure optimum crew health and hygiene. Computerized analysis and modeling techniques will be utilized throughout the program to evaluate and guide the development of appropriate life support technologies for long duration missions. Such techniques will also be used to integrate analytically and model complete physical-chemical life support systems prior to and in support of subsystem development and integration. Validated control and integration models will also enable the development of models for full simulation of life support systems in support of future mission operations.

Deliverables

PHASE I. By the early 1990s, some bread-board components for air revitalization, water reclamation, and a prototype regenerable, portable life support system which meet specific mission requirements will be available. Treatment of and water recovery from some wastes will require further process development. An analytically-based integration of the most promising candidate processes demonstrating a closed

physical-chemical life support concept, exclusive of food, will also be completed. Interaction and integration requirements of combined physical-chemical and biological subsystems will be under study.

PHASE II. All critical physical-chemical technologies providing for an essentially closed-loop life support system, exclusive of food production, will be developed and verified in an integrated subsystem testbed. Safety and reliability will be assured through the development of fault-tolerant system diagnostics and controls. Validated mathematical and heuristic models of the integrated physical-chemical subsystems will be developed and available to serve as the basis for development of operational models for system development and mission execution.

Crew-rated full scale system ground tests will be in progress for final validation of

integrated physical-chemical systems operation and model validation. The requirements of a first-generation combined physical-chemical-biological life support system will be defined.

4.5.4 Organization and Management

Work Breakdown Structure. The work breakdown structure is directed along major system functional lines. Figure 4-4 provides a preliminary WBS for the program.

Management Structure. The overall program will be managed by a program manager in the OAST Propulsion, Power and Energy Division (RP).

The lead center for development and implementation of a detailed technology project

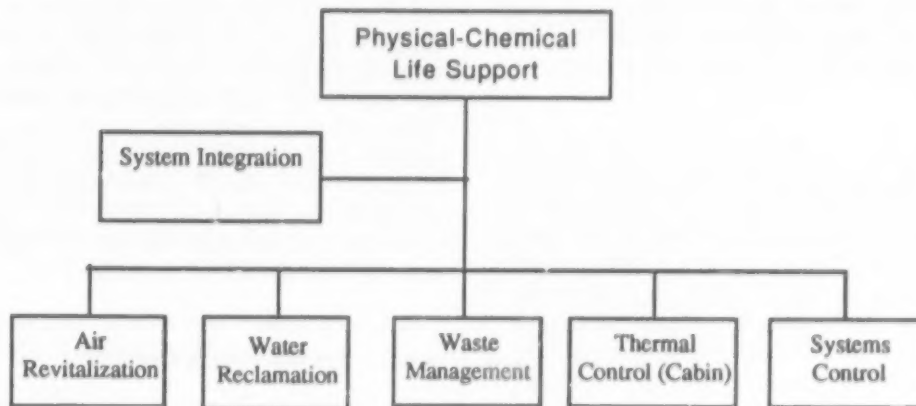


Figure 4-3
*Work Breakdown Structure for the Pathfinder
Physical-Chemical Life Support Technology Project*

Pathfinder

plan is the Ames Research Center. This center will have responsibility for leading the development of a project plan and for administration of the plan throughout the program. A technology project manager will be assigned at ARC for that purpose. All eventual participating centers will be responsible to the program manager in RP for all areas involving resources and program responsibility. They will be responsible to the lead center in administrative matters pertaining to annual planning, reporting, schedule and milestones.

Program Coordination. The Physical-Chemical Life Support (P-C Life Support) subprogram of Pathfinder will be closely coordinated with OSSA and OEXP. Within OAST, coordination will be maintained with RC in the areas of automation and expert systems and Pathfinder Extravehicular Activity/Suit program - from which work in portable life support systems will be funded. Coordination will also be maintained with RM vis-a-vis the Resource Processing Pilot Plant subprogram of Pathfinder, regarding the utilization of in situ resources for life support systems.

Resources. The P-C Life Support Technology Project will require, during the first phase of the program, resources of approximately \$36 million. The resource allocation to this effort for FY 1989 is \$1.75 million.

Section 4.6

Bioregenerative Life Support Requirements

4.6.1 Technology Requirements

The NASA Controlled Ecological Life Support System (CELSS) program was initiated with the premise that NASA's goals would eventually include extended-duration missions with sizable crews requiring capabilities beyond the ability of conventional life support technology. Currently, as mission duration and crew size increase, the mass and volume required for consumable life support supplies also increases linearly. Under these circumstances the logistics arrangements and associated costs for life support resupply will adversely affect the ability of NASA to conduct long-duration missions. A solution to the problem is to develop technology for the recycling of life support supplies from wastes. The CELSS concept is based upon the integration of biological and physical-chemical processes to construct a system which will produce food, potable water, and a breathable atmosphere from metabolic and other wastes in a stable and reliable manner. A central feature of a CELSS is the use of green plant photosynthesis to produce food, with the resulting production of oxygen and potable water and the removal of carbon dioxide.

4.6.2 Technology Assessment

The development of an operational CELSS will provide economic, psychological, and mission operations benefits. For long-duration missions, such as permanent Lunar or Mars bases where logistics supply is very costly or impractical, the development of a fully integrated bioregenerative life support system will be enabling. As the duration of

future manned space mission increases, a crossover point will be reached where it will be more economical to provide life support supplies by the recycling of metabolic and hygiene wastes than to incur the repeating costs of resupply. In-situ regeneration of life support consumables will protect the mission from unpredictable and potentially disastrous interruptions in the logistics train.

The availability of fresh foods such as grains, salad greens, and other vegetables, and the sense of autonomy inherent in a fully recycling life support system will have a positive effect upon crew psychology and productivity, thereby contributing to the ultimate success of the mission.

4.6.3 Program Description

Pathfinder will provide funding to study the engineering and performance requirement for advanced subsystem technologies needed to support food production, processing, and waste management in a bioregenerative life support system that will combine both biological and physical-chemical processes to recycle the food, air, and water needed to support long-term human missions in space.

A CELSS can be viewed as an integrated set of biological and physical-chemical subsystems, functioning through processes of regeneration and recycling to sustain human life. These major subsystems include:

1. Biomass production (plant and secondary animal production)
2. Biomass processing (food production from biomass)
3. Water purification
4. Air revitalization
5. Solid waste processing

6. System monitoring and control

These subsystems are interactive and interdependent.

Pathfinder will also increase support for Advanced Mission Studies directed at development mission specific technology requirements for CELSS applications for the suite of potential future manned missions.

Deliverables

PHASE I. Technology requirements will be determined for CELSS subsystems for crop plant growth, waste, and food processing.

PHASE II. Mission-specific bioregenerative life support system technology requirements will be determined.

PHASE III. The program will carry out a continuing study of advanced technologies that are needed to enhance the effectiveness of CELSS for advanced mission applications.

4.6.4 Organization and Management

Work Breakdown Structure. The work breakdown structure of the overall CELSS program is directed along major system functional lines. Figure 4-6 provides a preliminary WBS for the overall CELSS program. The Pathfinder Bioregenerative Life Support requirements subprogram will consider technology requirements in the areas of biological production, food processing, resource recycling and recovery, and advanced mission planning.

Management Structure. The overall program will be managed as noted in figure 4-

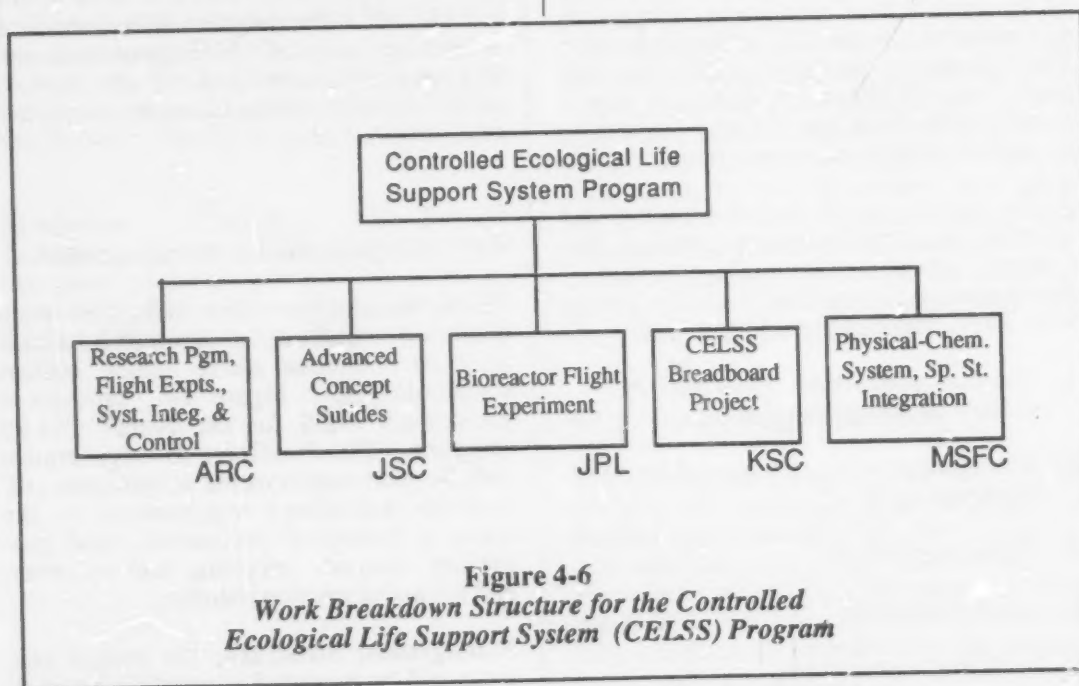
Pathfinder

6. The program Manager is located in the OSSA Life Sciences Division (EB), who assumes both program management and coordination responsibility for all aspects of the program. No lead center has been named, but participating centers have been given distinct roles and responsibilities in the areas of the CELSS program currently underway. Advice is provided by the Aerospace Medicine Advisory Committee (AMAC) within NASA, and by the Aeronautics and Space Engineering Board (ASEB) of the National Research Council (NRC) outside NASA.

Program Coordination. The CELSS program is integrated with programs in Space Medicine, Environmental Monitoring, Gravitational Biology, Biological Systems Research, and their related flight components with the EB. Coordination between the CELSS Program and the Physical-Chemical Life Support program with OAST

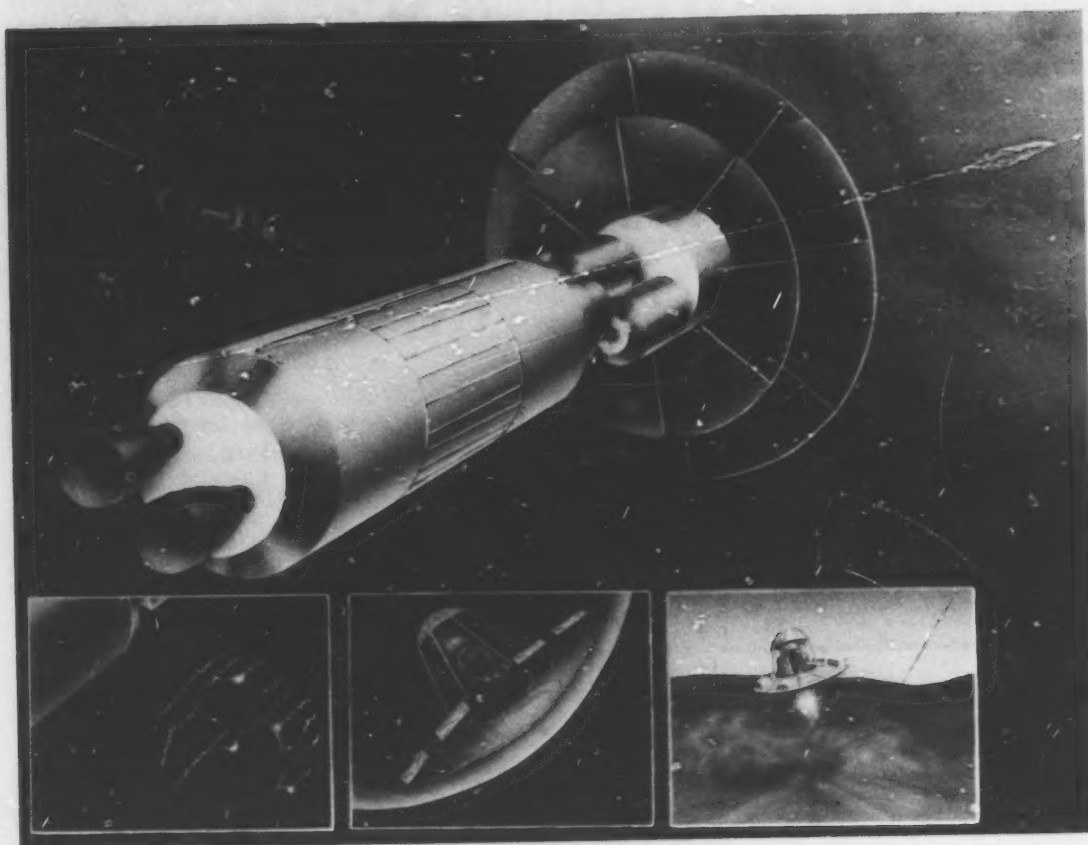
will be accomplished through direct contact at the Headquarters level, and at participating NASA Field Centers. The CELSS Program Manager in EB has also established a CELSS Coordinating Committee to provide a forum for intercenter contact among the CELSS program located at Ames Research Center, Johnson Space Flight Center, and the Kennedy Space Center. This Coordinating Committee also includes the participation of astronauts from Johnson Space Center.

Resources. Project Pathfinder Program resource requirements for this activity through Phase I are approximately \$6 million. Resource allocated for FY 1989 total \$250,000.





Pathfinder



Chapter 5 *Space Transfer*

The objective of the Space Transfer program area is to develop advanced space transfer capabilities that will enable or significantly enhance future piloted solar system exploration. The principal focus is on two functional capabilities: space propulsion and aerobraking.

The capability to move effectively from one orbit to another in space is a fundamental requirement for space operations. A variety of space transfer propulsion systems have served the needs of the civil space program since the 1960s, ranging in complexity from simple expendable upper stages, to the all-purpose service modules of the Apollo missions. Consistently, technology development programs in propulsion have sought improvements in engine performance (specific impulse and thrust) and advances in

engine reliability. To those longstanding goals, the advent of planning for the Space Shuttle and Space Station *Freedom* have added the objectives of reusability and space maintainability to the traditional list, as well as the goal of permanent space basing of space transfer systems.

Use of a planetary atmosphere to slow the speed and change the trajectory of spacecraft is another art that dates back to the 1960s. NASA's first efforts were the low life-to-drag (L/D) ratio Mercury, Gemini, and Apollo capsules; these used ablative heat shields to protect the mission's crews from the extreme heat of reentry.

Developed from those earlier technological foundations, the Space Shuttle represented a major advance in aeroassisted maneuvering. The Shuttle's winged-shape provides an extensive cross-range maneuvering capability during reentry, and its thermal protection tiles approach to the heating problem allows comparatively rapid operational turnaround

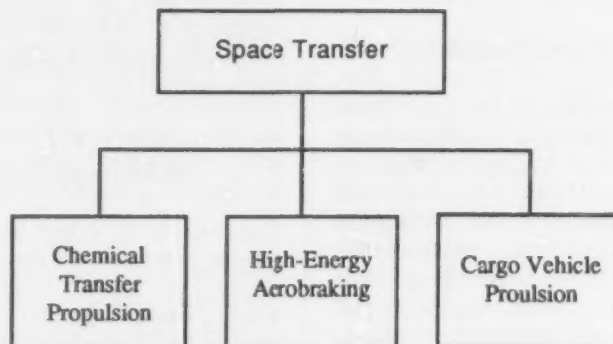


Figure 5
*Work Breakdown Structure for the Pathfinder
Space Transfer Program Area*

of the vehicle. At the same time, NASA was also applying Apollo-style aeroballistic entry techniques and ablative heat shields to the problem of entry and landing at Mars for the robotic Viking spacecraft in the late 1970s. Various studies have explored the possible use of these techniques to slow a spacecraft and modify its trajectory elegantly, without the use of propellant.

Pathfinder Space Transfer Efforts efforts consist of three technology projects. Two of those are in the area of advanced propulsion, and one is in the use of a planet's atmosphere in place of propellant. They are: (1) Chemical Transfer Propulsion, (2) High-Energy Aerobraking, and (3) Cargo Vehicle Propulsion.

Each of these is described in some detail in the subsections which follow.

Section 5.1

Chemical Transfer Propulsion

5.1.1 Technology Requirements

NASA's planning for future exploration of the solar system includes both robotic (precursor) and piloted missions to Mars, as well as a resumption of piloted missions to the Moon. One of the keys to reducing the cost of these missions is to minimize the propellant mass in LEO required to achieve a transfer trajectory, to accomplish orbit insertion, to effect a landing on the surface, and to return to earth. This propellant mass must be delivered to LEO by Earth-to-orbit (ETO) launch systems and the less propellant required in orbit to meet mission requirements means the fewer ETO vehicle launches.

A key enabling technology that will greatly reduce in-orbit propellant mass requirements is the development and use of high performance chemical propulsion systems for the transfer, orbit insertion, lander, and Earth return vehicles. Another key to reduced cost is to develop and utilize reusable transfer stages that are based in and operated from LEO. Technologies that will enable automated in-orbit operations, including refueling, maintenance, servicing, and preflight systems checkout, as well as fault-tolerant in-flight operations, are critical to the successful development and use of space-based vehicle systems.

In the case of the manned Mars mission, an increase of 35 seconds of engine specific impulse (Isp) saves the cost of at least two ETO vehicle launches assuming the transfer stage is expended. In addition, the propulsion systems developed for the Mars and lunar missions will also be applicable to LEO to GEO and return orbital transfer vehicles and to transfer stages needed for the precursor unmanned missions to Mars. For lander vehicles, deep throttling by the lander engine is required for both hovering and landing. High engine performance over a wide throttle range will result in a significant savings in propellant mass required to effect a successful safe landing.

5.1.2 Technology Assessment

The only U.S. upper stage LOX/Hydrogen engine currently in operation is the highly successful RL10 expander cycle engine which was developed and certified in the late 1950s and early 1960s. However, the RL-10 is a low pressure engine that delivers only moderate performance, has limited throttling capability and no onboard diagnostics. It was designed for and has been used only on expendable vehicles.

5.1.3 Program Description

The Pathfinder Chemical Transfer Propulsion Program is geared to establish the technology base that will enable the development of high performance chemical transfer propulsion systems that can be space-based, as well as lander propulsion systems that can provide the needed high performance over a wide throttle range. A LOX/Hydrogen expander cycle engine has been identified as the primary candidate propulsion system that will meet these stringent mission requirements.

Critical technologies will be developed in the areas of high performance variable flow components, high expansion ratio nozzle flow characterization, design for in-space maintainability, and integrated health monitoring/ control systems that will provide automated preflight operations, as well as fault-tolerant engine flight operations. The objective of the program is to validate high performance expander cycle engine concepts, including high pressure cycle balance demonstrations, component interaction predictions, engine controls (including deep throttling), and system level health monitoring diagnostic capabilities for basing in space.

The Chemical Transfer Propulsion program will use a building block approach ranging from fundamental technologies through component, subsystem, and system technology hardware demonstrations. Work in the R&T Base over the past few years has been directed towards establishing engine design concepts capable of meeting expected mission requirements and pursuing critical technology advances necessary for those



Conceptual illustration of an automated chemical transfer vehicle entering Lunar orbit

engine concepts to achieve performance, life, and operational goals. Advanced design concepts and analytical methods have been developed using laboratory and especially designed test equipment to generate the data base needed for design verification and code validation.

The Chemical Transfer Propulsion program will build on the R&T Base results by moving progressively through full scale component, subsystem, and system level validation and demonstration programs. Key milestones include 1) documented validation of full scale component hardware designs and analytical methods, including turbomachinery, thrust chamber assemblies, valves and controls, and integrated diagnostic sensors; 2) the development and demonstration of engine performance and dynamics models utilizing an integrated component breadboard engine assembly for cycle and concept validation testing; and 3) the demonstration of fault-tolerant engine operations, component life, and automated preflight operations utilizing advanced

component designs that will be developed to meet Mars and Lunar mission requirements and then incorporated into the breadboard engine. When the technology program is complete, the operational hardware will then be available to support further engine development as an offline testbed for problem solving and product improvement.

The technical program will be supported by engine system level design and analysis efforts in order to compare the impact of technology advances on the assumptions originally made in the earlier concept definition studies. In addition, mission study activities being conducted by OEXP will be used to identify mission dependent propulsion requirements.

Deliverables

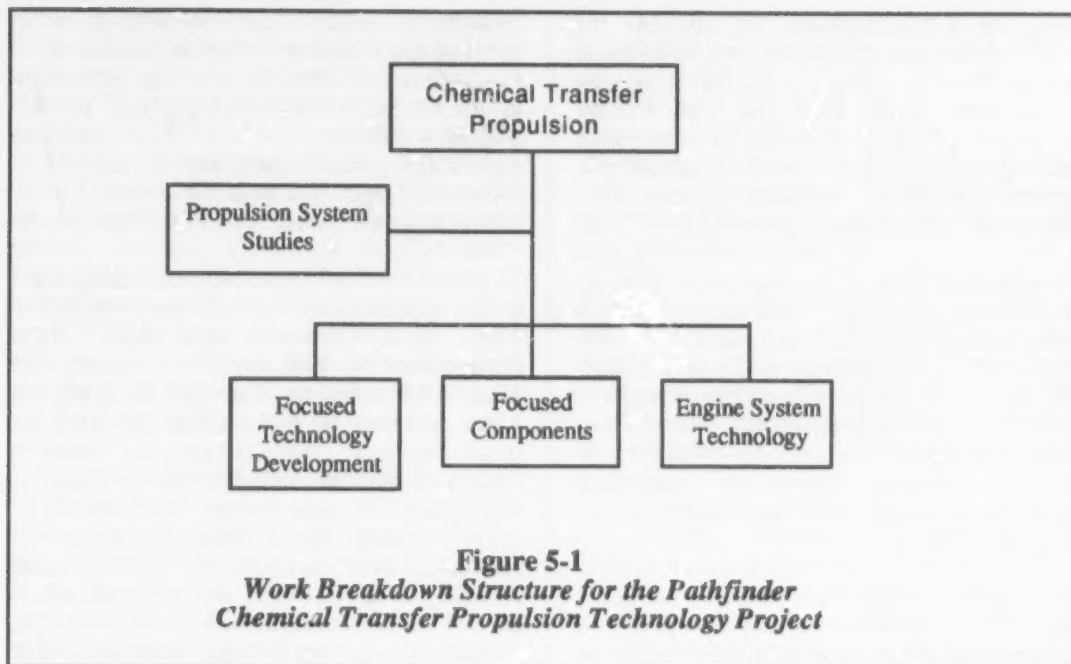
PHASE I. The first phase of this focused program will be directed toward component and subsystem level advanced design and analysis development and verification. Advanced design concepts and analytical methods that have been previously developed in the R&T Base Program utilizing laboratory, bench, and rig testing will be used in the design and fabrication of component and subsystem hardware. This highly instrumented hardware will be operated over a wide range of conditions for design verification and refinement. The output of this phase of the program will be computational codes capable of predicting component and subsystem performance, life, dynamics, and operating characteristics, as well as a broad experimental data base. This effort will also support the potential initiation in FY 1990 of an advanced development program funded by OSF. The purpose is to demonstrate a near prototype engine that could be developed for an early Space Transfer Vehicle (STV), designed to meet the requirements of planned high energy solar system science exploration missions. The

design of this engine would be based on the component and subsystem technology being developed in the OAST program.

A parallel effort in Phase I will be directed toward developing design methodology for advanced components incorporating the necessary features, design characteristics, and diagnostics that will lead to the definition and demonstration of highly reliable, space-based, high-performance, throttleable engines capable of meeting future Mars/Lunar transfer, lander, ascent, and Earth return vehicle requirements.

PHASE II. The demonstrated components and subsystems from Phase I will be assembled into an early breadboard engine configuration in order to conduct component interaction and system level verification testing, and to establish a system level experimental data base. High pressure expander cycle operation will be validated, and engine models for predicting transient, steady state, and throttling performance will be tested, refined, and verified. The fabrication and verification testing of advanced components designed on the basis of the parallel Phase I focused technology program will also be completed during this phase.

PHASE III. The third phase of the program will follow with the overall objective of demonstrating the performance, life, and transient/steady state operation of a breadboard engine system incorporating the advanced components from Phase II. The engine will have all the design, performance, and operational characteristics needed to meet the requirements of space-based transfer, lander, ascent, and Earth return vehicles, including automated preflight operations, in-space maintainability, and fault-tolerant flight operations. When this phase of the program is complete, the hardware will be available for use in further engine development as a testbed for problem solving and for product



improvement activities. The projected completion date is FY 1997.

5.1.4 Organization and Management

Work Breakdown Structure. The program is organized as shown in Figure 5-1. The work breakdown structure allows work to be focused in several critical areas and also provides a flow mechanism for raising the technology to higher and higher hardware definition levels, while focusing the technology results into engine system level analysis studies in order to assess progress towards program goals and milestones.

Management Structure. The headquarters program manager will be located in the OAST Propulsion, Power, and Energy Division (RP). In addition to program management responsibilities, the program

manager will be responsible for carrying out the coordination activities described below.

The LeRC will be the lead center for the Chemical Transfer Propulsion program. The roles of other participating centers will be established during the course of detail planning over the next several months. As mentioned previously, an inter-center/interagency technical advisory committee that was established under the R&T Base program will continue to function in that capacity.

There is currently an active ad hoc subcommittee under the Space Systems and Technology Advisory Committee (SSTAC) that is evaluating and assessing propulsion candidates for planetary missions. The results of their assessment will be used in planning the Pathfinder propulsion programs.

Program Coordination. In addition to coordination with OEXP relative to mission studies, the program will be also be coordinated with OSF as the future developer of space transfer vehicles, and with OSSA in order to incorporate unmanned planetary mission drivers into propulsion technology requirements.

Coordination with DoD agencies will be maintained through normal program coordination activities, including the Joint Army, Navy, NASA, Air Force (JANNAF) Interagency Propulsion Committee, and the NASA/AF Space Technology Inter-dependency Group (STIG). In addition, a technical advisory committee supporting the project manager will have an active Air Force member.

Resources. Projected resource requirements for this activity for the first phase of the program are approximately \$64 million. Resources allocated in FY 1989 are \$4 million.

Section 5.2

High-Energy Aerobraking

5.2.1 Technology Requirements

NASA's planning for the future exploration of the solar system includes both piloted and robotic missions to Mars. The success of these as well as other planetary missions will depend upon maximizing the non-propellant mass for the mission in LEO (LEO), on the planetary surface, and for return to Earth. All of these are limited by current launch vehicle capabilities. A key enabling technology that promises to increase the payload-to-propellant mass ratio is high-energy aerobraking. Through the development and use of aerobraking

techniques rather than retropropulsion to achieve deceleration for orbit modification (i.e., transition from a transfer orbit to a circular orbit), substantial payload to propellant advantages will be realized. Aerobraking techniques may be utilized at either the target (for example, Mars), if the planet has an atmosphere, or at Earth return.

In the case of a Mars rover and sample return mission, the use of aerobraking at Mars could reduce total LEO mass requirement by 50% over an all-propulsive Mars orbit insertion. The case for a piloted Mars mission is more complex, and the mass savings depends on the mission launch date and whether the vehicle is configured for zero gravity or for artificial gravity during transit. Given a zero gravity spacecraft configuration, the required mass to LEO for an all-propulsive mission would be 2-4 million pounds, compared with 1-2 pounds for an aerobraking mission. The propellant mass savings and increased payload capability associated with aerobraking is very significant.

Although Earth's atmosphere is well characterized, uncertainties exist regarding variations in the properties of the atmosphere of Mars (and other planets). However, round trip light time communications delays will preclude the possibility of effective ground-based adjustments of planetary aerocapture operations. In the case of a Mars mission R'TLT delays can be on the order of twenty minutes. Therefore, planetary aerocapture (e.g., at Mars) will require onboard, realtime GN&C capabilities that can adapt to atmospheric uncertainties.

5.2.2 Technology Assessment

At present, no validated aerobraking capability exists. Apollo and Shuttle experiences, based on low and mid L/D (lift over drag), simple blunt configuration operating

over narrow reentry corridors, provide a limited database relative to aeromaneuvering and/or aerobraking techniques. The two robotic Viking spacecraft that landed safely on Mars in 1976 did not have the capability to be precisely targeted at sites on the surface. This limitation would increase the risk and sharply reduce the scientific return of a piloted or robotic Mars mission. The Aero-assist Flight Experiment (AFE) will provide a database aimed at validating aerobraking for GEO and lunar return conditions. This will be a significant step toward understanding aerobraking at conditions compatible to Mars entry velocity.

However, technology issues will still need to be resolved in a number of areas. The effects of long term exposure of TPS materials to the space environment have not been precisely defined. In addition, advanced TPS designs (ablative, volume reflecting, etc.) that will accommodate very high velocity/high enthalpy flow conditions have not been adequately evaluated or developed.

In another area, the ability to handle "new" atmospheric constituents such as carbon dioxide, nitrogen, and argon has not been incorporated into current CFD codes. Gas chemistry models which can provide accurate prediction of aerodynamic and aerothermal loads in these environments are not yet being developed.

The ability to identify and compensate for large variations and fluctuations in both Earth and Mars atmospheric constituents and densities is needed. This will reduce the burden carried by the realtime, fault-tolerant, adaptive GN&C and flight mechanics systems.

In general, mission requirements and system design trades for piloted and robotic missions involving planetary entry aeromaneuvering and high-speed Earth reentry are not well-defined or understood.

Military capabilities for ballistic missile reentry and GN&C are sophisticated and have been well-demonstrated. However, the characteristics of solar system exploration mission aerobraking applications at Earth (e.g., a large piloted spacecraft) - and the requirement for aerobraking at other planets - limit the *a priori* application of those technologies to civil space missions.



Conceptual illustration of three classes of planetary aerobraking problems

5.2.3 Program Description

The program will be planned and implemented in two broadly defined phases. The first

Pathfinder

will be a technology development phase which will result in the definition of selected aeroassist vehicle concepts and the definition of a flight experiment. The second phase will be a technology demonstration phase culminating in a high-energy aerobraking flight experiment.

The goal of phase I of the Pathfinder High-Energy Aerobraking Program is to develop the enabling technology base required to perform high-velocity aerocapture and aeromaneuvering, with resultant substantial reductions in mission LEO mass requirements. In order to achieve this goal, the program will be designed to achieve the following objectives:

- (1) Establish mission constraints and requirements for planetary aerobraking (including aerocapture, aeromaneuvering entry, and orbit to orbit aerobraking)
- (2) Develop and improve Computational Fluid Dynamics (CFD) codes for prediction of aerodynamic and aeroheating environments for planetary and high-energy Earth aerobraking.
- (3) Develop and validate fault-tolerant GN&C technology for planetary and high-energy Earth aerobraking.
- (4) Evaluate advanced Thermal Protection System (TPS) materials and designs.

In addition, requirements and concepts will be formulated for potential technology flight experiments to validate high-energy aerobraking at Earth return.

Overall vehicle configuration analyses and system design trades - which will be used to integrate discipline objectives - will be supported by appropriate ground testing. As a result of the above efforts, baseline vehicle concepts for both a piloted Mars mission and a Mars rover and sample return mission will be defined.

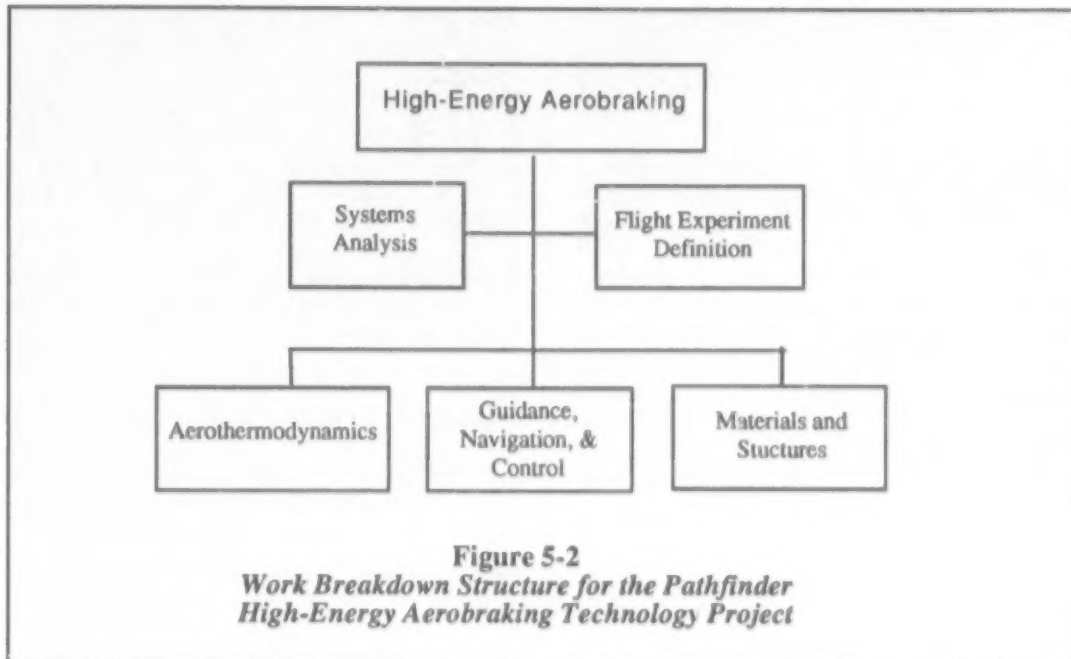
Flight validation in a Planetary Return Flight Experiment (PRFE) will be considered in phase II of the overall High Energy Aerobraking Program, and would be implemented in coordination with the CSTI Aeroassist Flight Experiment (AFE) Program. The information obtained from PRFE, complemented by the data obtained from AFE, should provide a significant data base for a wide range of aerobrake applications.

The High-Energy Aerobraking Program will encompass a broad range of technical disciplines, each at varying levels of technology readiness and maturity. As a consequence, the technical approach to implementation will involve a family of related discipline-directed efforts, coordinated through a Headquarters/ Inter-Center working group (see the discussion below). Fundamental research in the areas of TPS and aerodynamics and aerothermodynamics will be balanced against more focused efforts in GN&C algorithm and system development.

The program will be integrated through initial mission analyses and requirements studies, and through later system design trades and integration studies. These activities will also support the definition of a planetary return flight experiment.

Deliverables

PHASE I. By the early to mid 1990s, critical technologies will be developed to the point of defining reasonable margins in aerobrake configurations, aerodynamics and aerothermodynamics, flight mechanics and controls, and TPS designs. Improved computational flow codes for both Earth and Mars atmospheres and engineering design capability will be available. TPS design trades will be completed, and materials, cooling mechanisms, and



structural concepts will be developed and evaluated. Advanced control algorithms will be established and adaptive GN&C systems will be validated. As a result of the above, baseline vehicle concepts for both a piloted Mars mission and a robotic mission (such as a Mars rover and sample return) will be defined.

PHASE II. By the mid to late 1990s, all key high-energy aerobraking/aeromaneuvering technologies will have reached a state of maturity that will permit a (high-energy) PRFE to be defined and conducted. To the greatest extent possible, this experiment will be built on AFE experiences, flight data, and, where appropriate, flight hardware and instrumentation.

5.2.4 Organization and Management

Work Breakdown Structure. This program is organized primarily along discipline lines, with specific cross-cutting tasks identified to integrate the discipline efforts.

Figure 5-2 provides the preliminary work breakdown structure for the program. This WBS will be revised and refined during the course of the next several months of detailed program planning.

Management Structure. The High-Energy Aerobraking Program will be managed by a Program Manager in the Aerodynamic Division of OAST (RF). Coordination between the various discipline efforts within the program will be provided through a High-Energy Aerobraking management oversight committee which is comprised of representatives from the several OAST discipline Divisions and the

Pathfinder

Space Directorate (RS). Responsibility for center assignments, project plan approval and funding allocation will remain with the RF Program Manager.

A lead center will be assigned, and a Technology Project Manager appointed at that lead center. NASA centers will be designated to implement specific tasks within the technology project. Technology Project planning, integration and reporting will be performed by the Field Center Technology Project Manager. Quarterly technology project reports will be submitted to OAST which track progress against Level 1 schedules and identify any problems, issues, or significant accomplishments.

Program Coordination. As noted above, this program will be coordinated with the ongoing AFE program within CSTI. The program will be more generally coordinated with appropriate personnel in OSF (as indicated in the Management Structure provided below). The program will also be coordinated with the OAST Power and Propulsion Division (in particular in the area of vehicle configuration definition).

In addition to mission analyses and requirements definition within the program, the High-Energy Aerobraking Program will be coordinated with (1) the piloted exploration mission definition studies of OEXP, and (2) the Mars rover and sample return mission studies being conducted by OSSA. Specific mission studies or opportunities for mission enhancements through technology applications will be recommended to those offices.

This program will also seek coordination with space computing technology developments because some approaches may require realtime, onboard processing capabilities.

This program will be coordinated with the other programs in Pathfinder through the respective Headquarters subprogram Managers. In particular, the GN&C aspects of this program will be coordinated with the corresponding areas of the Autonomous Lander Program and the Autonomous Rendezvous and Docking Program.

Coordination will be maintained with the relevant aspects of Department of Defense (DoD) programs.

Resources. Resource requirements for this activity for the first phase of the program are approximately \$46 million. The resource allocation for FY 1989 is \$1.5 million.

Section 5.3 *Cargo Vehicle Propulsion*

5.3.1 Technology Requirements

The cost - proportional to the mass - of placing any spacecraft in LEO is a major fraction of the total cost of a mission. Increasingly, propellant is becoming the dominant mass for NASA space missions. For example, in the case of the Galileo mission, propellant accounts for 43% of the total mass of the spacecraft in LEO. For the more challenging Comet Rendezvous/Asteroid Flyby (CRAF) mission, chemical propellant makes up 76% of the LEO mass of the spacecraft.

The still more challenging missions that are being considered for the future, such as Mars, will place even greater demands on spacecraft propulsion system technology.

Studies have shown that for a cargo vehicle

supporting a piloted mission to Mars, high performance electric propulsion with a specific impulse over 4,000 seconds at multi-megawatt power levels can offer major reductions in total propellant mass requirements, while still providing acceptable transit time performance. Compared with a chemically-propelled (cryogenic hydrogen/oxygen) cargo vehicle using aerocapture at Mars, a non-aerobraking, high performance electric propulsion vehicle could reduce total mission mass required in LEO by an amount equivalent to at least three Heavy Lift Launch Vehicles (HLLVs). The reduction in launched mass is obviously even greater for a non-aerobraking, completely propulsive chemically propelled cargo vehicle.

High specific impulse clearly offers propellant mass savings. However, in order to exploit this benefit practically, it is essential that the overall vehicle exhibit acceleration levels - and resultant transit times - sufficient to meet acceptable overall mission timeframes. This requirement ne-

cessitates low specific mass and high efficiency propulsion in order to keep low power system mass. High total impulse and high power capability per engine is also needed in order to accomplish mission propulsion system performance requirements with an acceptable number of individual engines.

5.3.2 Technology Assessment

At the present time, the only operation uses of electric propulsion have been low power systems used to perform satellite station-keeping functions. Since Isp over 4,000 seconds are of interest for Pathfinder, electrothermal systems such as arcjets are not adequate even with hydrogen propellant (Isp < 1,500 seconds). Advanced concepts such as electrodeless thruster systems may ultimately provide the desired characteristics, but do not have sufficient technical maturity to be considered during the initial years of Pathfinder.



A nuclear electric propulsion driven cargo vehicle enters Mars' orbit

Ion engines have demonstrated specific impulses from less than 2,000 seconds to more than 10,000 seconds, thrust efficiencies to over 75%, and total thrust impulses as high as 10^6 newton-seconds for 10 kW class thrusters. Key issues are scale-up of ion acceleration subsystems for high power operation, increasing the power density to reduce the number of engines required, and thrust (or life).

Magnetoplasmadynamic (MPD) propulsion technology is generally less advanced than ion systems. Power levels of 5 MW have been demonstrated in a pulsed power mode, but levels of only about 250 kW have been demonstrated for steady power. Most of the efficiency data fall into the 15-30% range, although some data for hydrogen and lithium propellants approach 50% efficiency at very low power levels. Higher efficiencies and specific impulses are generally obtained with applied magnetic fields, but a fundamental theoretical understanding of this mode of operation is lacking. The highest total impulse demonstrated is 10^6 newton-seconds, at about 25 kW. Key technology issues are thruster efficiency and life.

Facility background composition and pressure have been shown in some cases to have a very significant (factor greater than two) impact on measured performance. The impact of facility effects and the availability of enough high-fidelity ground test facilities are serious issues in the further development of high-power, high-performance electric propulsion systems.

5.3.3 Program Description

The Pathfinder Cargo Vehicle Propulsion Program will establish the feasibility and practicality of electric propulsion for piloted and robotic solar system exploration. The performance objectives of the program are: high specific impulse - over 4,000 seconds - high efficiency - over 60% - and acceptable life. The electric propulsion technologies developed must also be scalable to multi-megawatt power levels. Sufficient durability will be targeted to enable a total impulse

on the order of 10^8 newton-seconds per engine. Following preliminary development and testing, the most promising candidate thruster (ion or MPD) will be selected for further development.

The Cargo Vehicle Propulsion program will concentrate on performance and critical feasibility issues for the candidate thrusters. The first step will be to assess facility impacts on high-fidelity performance and durability data. Reliable short term, in situ methods of evaluating life issues will be developed along with the required facility capabilities so that performance limits can be established for each thruster. Parallel thruster technology efforts will be performed for both self-field and applied-field MPD thrusters as well as ion engines. It is necessary to devote most of the resources early in the program to MPD development, because of its much greater technical uncertainties. Power processor technology will be directed to provide laboratory-class hardware. Supporting thermal and systems analyses will be included in the program, while mission studies will be provided from outside sources.

A three-phase program is envisioned. Phase I will cover the first five years of the effort. It will be devoted to establishing feasibility and practicality and will culminate in selection of the most promising of several candidate electric propulsion concepts for further development. Phase I will be completed at the end of 1993.

Phase II will be a 5-year focused technology program that will demonstrate performance and life at high power levels and define requirements for a technology flight demonstration. If required, Phase III will be a flight validation of high-performance, high power electric propulsion technology.

5.3.4 Organization and Management

Work Breakdown Structure. A work breakdown structure for the program is

Space Transfer

shown in Figure 5-3. This WBS is applicable to Phase I of the program, consistent with the technical approach described above. This WBS will be revised and refined during the course of detailed planning during the next several months.

Management Structure. The program will be managed by a program manager in the OAST Propulsion, Power and Energy Division (RP).

LeRC will act as the lead center for the program, with responsibility for technical integration and reporting; this function will be performed by the Low Thrust Propulsion Branch. Responsibility for assignment of participating center responsibilities and resource allocation decisions will remain with the OAST program manager. Program efforts will be implemented by LeRC and JPL.

Program Coordination. In addition to coordination with OEXP and OSSA, the Cargo Vehicle Propulsion Program will be coordinated with related programs in Pathfinder - including the Space Nuclear Power Program (SP-100) - and with related national activities, such as those within the Strategic Defense Initiative Organization (SDIO).

The program will be supported by and coordinated with mission studies conducted by the LeRC Advanced Systems Analysis Office (ASAO) for OEXP and planetary mission studies conducted by the Advanced Systems Analysis Group at JPL for OSSA.

Resources. Projected resource requirements for the Cargo Vehicle Propulsion Technology Project for the first phase of the program are approximately \$16 million.

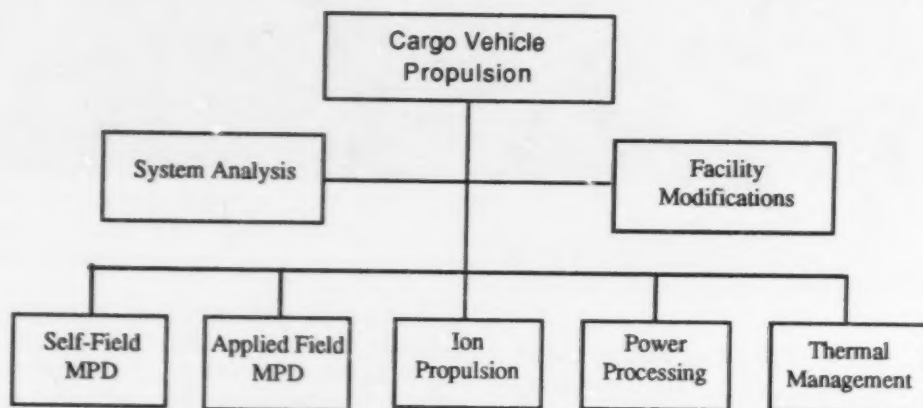


Figure 5-3
*Work Breakdown Structure for the Pathfinder
Cargo Vehicle Propulsion Technology Project*

Pathfinder



Chapter 6

Mission Studies

NASA is currently conducting several solar system exploration mission studies activities. The Office of Exploration is examining options for human exploration, while the Office of Space Science and Application's Solar System Exploration Division is studying future robotic exploration missions. Studies of robotic precursors to human missions - such as a Mars rover and sample return mission - are being jointly evaluated by OEXP and OSSA.

Section 6.1

Introduction

The mission studies being conducted by OEXP are extending the preliminary mission definition results described in the 1987 report *Leadership and America's Future in Space* by Dr. Sally K. Ride. OEXP's mission studies will provide greater understanding of the *Leadership* report's "bold new initiatives" and will explore other potential options.

This detailed understanding of each mission and the various options necessary to accomplish it are essential prerequisites to the selection and advocacy of a civil space leadership initiative. Studies of human mission options will also identify the scientific opportunities that can be supported by each mission and the requirements those opportunities place on the mission scenarios. Finally, OEXP's mission studies will identify and quantify the tech-

nology requirements for each mission option and will conduct systematic tradeoff studies between alternate technologies.

The mission studies will include mission-level assessments and focused activities in areas such as in-space transfer vehicles, operations requirements at various nodes such as Earth, Mars, and Lunar orbits, and Mars and Lunar surface operations. In addition, the studies will assess the leverage inherent in systems and technologies for power, propulsion, life support, and automation & robotics.



Other offices in NASA, such as the Office of Space Station and the Office of Space Flight are examining how their programs and plans would be affected by future solar system exploration missions.

Pathfinder

Section 6.2 Human Exploration Case Studies

In Fiscal Year 1988, OEXP mission studies focused on four specific case studies of potential human exploration initiatives. These were: (1) a human expedition to Phobos (a moon of Mars), (2) a human expedition to the surface of Mars, (3) installation and operation of human-tended scientific observa-



tories on the Moon, and (4) an evolutionary extension of human presence, starting with an outpost on the Moon and building toward missions to Mars.

Through these human exploration case studies, which are partially funded by the current Pathfinder Mission Studies program area, OEXP is identifying and clarifying the various program planning changes and technology requirements that NASA must satisfy in order to achieve those ambitious civil space objectives.

6.2.1 Human Expedition to Phobos

This case study examines the options for the first and/or fastest human mission to the Mars system. An initiative following along the lines delineated in this case study would result in a human landing on this moon of Mars by the 2003 timeframe. In terms of impacts on other NASA programs, this case has identified only minimal requirements that would be imposed on an Earth-orbiting Space Station. ETO launch capabilities would require substantial augmentation to meet the preliminary needs that have been identified.

Technology requirements to achieve the objectives identified by the Phobos case study are minimal, but include (1) assembly and integration of vehicle systems in Earth orbit, (2) extravehicular activity (EVA) suits and systems for Phobos proximity operations, (3) In-Space cryogenic fueling of mission vehicles, and (4) tele-robotic rovers that would be landed on the surface of Mars and controlled by astronauts in Mars' orbit. Aerobraking is being considered as a possible mission option.

6.2.2 Human Expeditions to Mars

This case study examines the options for the first human mission to the surface of Mars. A future initiative following this sort of mission approach would result in a human landing on Mars by the 2008 timeframe. This case would involve substantial requirements for ETO launch capabilities, and an

Mission Studies

Earth-orbiting Space Station, including both mission staging and premission research and development of essential technology and determining the effects of long-duration space flight on humans.

Technology requirements to achieve the objectives that have been identified by the Mars expedition case study include (1) tele-robotic assembly and automated integration of vehicle systems in Earth orbit, (2) extravehicular activity (EVA) suits and systems for Mars surface operations, (3) In-space cryogenic fueling of mission vehicles, (4) interplanetary aerocapture technologies, and (5) advanced space propulsion systems.

As a potential precursor to a piloted flight, a robotic mission to Mars would involve semi-autonomous rovers that would be landed on the surface of Mars, and controlled from Earth.

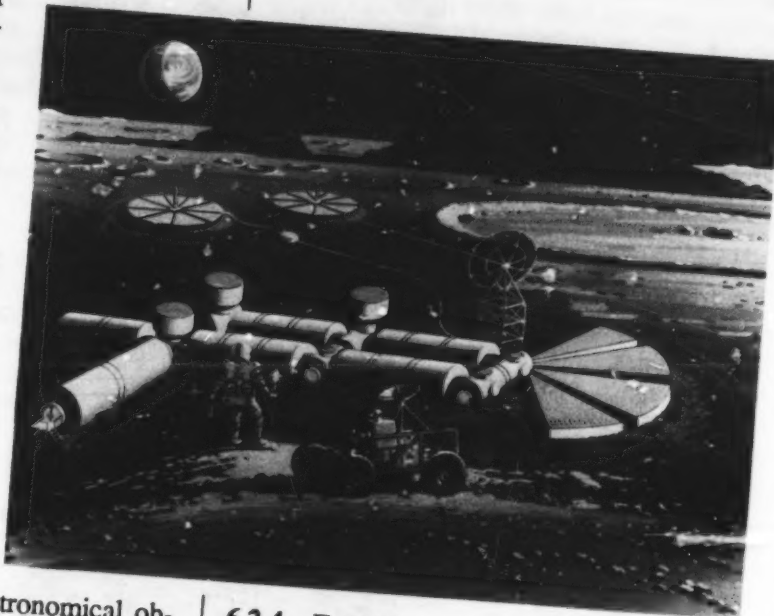
6.2.3 Lunar Observatories

The Lunar observatories case study examines the options for deployment and operation of a major astronomical observatory on the Moon. This case has examined issues associated with an initial mission by the year 2000 timeframe; it would involve both some increase in ETO capabilities and requirements for an Earth-orbiting Space Station.

To achieve the objectives that have been identified through the Lunar Observatories case study, technology requirements include (1) automated integration of vehicle systems in Earth orbit, (2) extravehicular

activity (EVA) suits and systems for the Lunar surface, and (3) surface power systems (potentially including space nuclear power and mobile power for Lunar rover and equipment).

As a potential precursor to a piloted flight, robotic missions to the Moon might involve Lunar orbiters and semiautonomous or teleoperated rovers that would be landed on the surface of Mars and controlled from Earth.



6.2.4 Evolution: Lunar Outpost to Early Mars Outpost

This case study examines the options for an evolutionary program that would start with a return to the Moon to build an outpost and lead ultimately to an outpost on the surface of Mars. By assumption, this case study limits launch capability projects. That assumption constrains the rate at which the case develops and forces innovative approaches. A potential initiative constructed along the lines explored in this case study

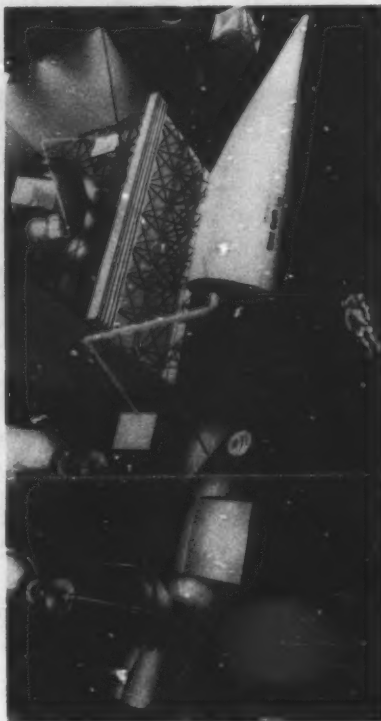
would result in a permanent, self-sustaining human presence beyond low Earth orbit (LEO). This case would involve substantial requirements for an Earth-orbiting Space Station, and more advanced orbiting "nodes," including both mission staging and pre-mission research on the effects of long-duration flight on humans.

Technology requirements to achieve the objectives of the evolutionary expansion case study are very broad. These requirements include (1) telerobotic assembly and automated integration of vehicle systems in Earth orbit, (2) extravehicular activity (EVA) suits and systems for Lunar and Mars surface operations, (3) In-space cryogenic fueling of mission vehicles, (4) reusable interplanetary aerocapture technologies, (5) advanced space propulsion systems, including nuclear electric propulsion, (6) in situ resource processing (and propellant production), and (7) advanced life support systems.

As potential precursors to later piloted expeditions, robotic missions to the Moon or Mars would involve semiautonomous rovers that would be landed on the planetary surface and controlled from both Earth and orbit. A broad array of additional technologies would be needed to implement successfully an evolutionary set of robotic precursor missions.

6.2.5 Future Exploration Case Studies

In Fiscal Year 1989, OEXP cases studies include (1) a reevaluation of an evolutionary expansion through a Lunar Outpost, with an ultimate goal of Mars, (2) using Phobos as a "gateway" to reach long-term operations on the surface of Mars, and (3) a small expeditionary mission directly to Mars.



Detailed technology requirements for these revised case studies will be defined during the course of FY 1989, and documented in the OEXP annual report at the end of the year; they are not available at the present time.

Section 6.3 Robotic Solar System Exploration Mission Studies

NASA has a long standing tradition of excellence in robotic Solar System exploration. In the future, NASA plans to continue that tradition, both to further our attempts to understand our planetary system, its origin, and its evolution,

and also to provide robotic precursors to later human exploration expeditions.

A broad assortment of robotic mission options are currently under consideration. These span the gamut from more near term opportunities (with little or no needs for Pathfinder technologies), to sophisticated and ambitious far-term mission concepts that may involve returning samples to Earth

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for intensive study (with strong technology requirements).

6.3.1 Near Term Mission Options

The prospects are bright for an exciting period of robotic exploration in the coming years. The Magellan spacecraft should be launched shortly, providing high resolution radar imagery of the cloud-hidden surface of Venus. The Mars Observer mission will also be launched in the near future, providing substantially improved imaging and science data about Mars. Mid term future options include applications of the Mariner Mark II spacecraft series. These are the Comet Rendezvous Asteroid Flyby (CRAF) mission, which would study both a Main Belt asteroid and a comet; and the Cassini mission, which would orbit Saturn and provide comprehensive studies of its largest moon, Titan.

Both of these missions are slated for a new start decision in the 1990-91 timeframe, and would be built and launched by the mid to late 1990s. Although exciting, both of these missions will probably be implemented before Pathfinder technologies are available for application.

6.3.2 Sample Return Missions

Farther out on the horizon, a pinnacle of robotic exploration will be reached through one or more (surface and subsurface) sample return missions. The primary options for such mission concepts are the Comet Nucleus Sample Return (CNSR) mission, and a Mars Rover and Sample Return (MRSR) mission. Missions such as these will require advances in automation and robotics, in situ analysis and sample preservation, and in space transfer technologies, such as aerocapture at Earth return.

Either of these missions could be started in

the mid to late 1990s timeframe, and could be built and launched by the early part of the next century.

Comet Nucleus Sample Return (CNSR). The CNSR mission concept is being studied by both the Office of Space Science and Applications of NASA, and by the European Space Agency (ESA). Building upon the foundation established by the CRAF mission, a CNSR mission would return samples taken by a small lander from the core (or nucleus) of a comet. Mission scenarios under study include the adaptation of systems from the Mariner Mark II spacecraft series, using advanced technologies (such as those developed in Pathfinder).

Technologies that would be needed for a robotic CNSR mission include rendezvous and "docking" with the comet, precision guidance and hazard avoidance during landing, sample acquisition and preservation, rendezvous and docking in the vicinity of the comet, and successful high-energy aerocapture at Earth return.

Mars Rover and Sample Return (MRSR). The MRSR mission concept is being studied by both the Office of Exploration and the Office of Space Science and Applications. One or more robotic missions to Mars represent both a scientific opportunity, but - and perhaps more important - also a technology demonstration opportunity. Unlike the Apollo Program, a piloted Mars mission program will not have the luxury of multiple trial flights, during which various technologies and new capabilities could be proven prior to a commitment to a landing on the surface. Because of the distances and resultant flight times involved, a piloted mission to Mars may only be preceded by one or more robotic flights such as the MRSR concept.

Technologies that could be validated during

Pathfinder

a robotic mission include aerocapture at Mars, precision guidance and hazard avoidance during landing, surface mobility systems, ascent propulsion and rendezvous in Mars orbit, and successful high-energy aerocapture at Earth return.

6.3.3 Outer Planet Missions

Future mission options will also include follow-on missions to the enormously successful Voyager program, that flew spacecraft by Jupiter, Saturn, and Uranus, and which should reach Neptune next summer. Currently ready to be launched, the Galileo spacecraft that will orbit Jupiter. The projected Cassini mission to Saturn. Further in the future, advanced outer planet missions could involve orbiters of the far outer planets (Uranus and Neptune) or a flyby of the solar system's most distant goal, the Pluto-Charon system.

Technology requirements for such missions include those which are common to many others, such as planetary aerobraking, advanced space communications (e.g., optical communications), increased spacecraft onboard computing and autonomy, and higher levels of onboard power. They also include more mission-specific technology options, such as nuclear electric propulsion (NEP), which would substantially augment mission capabilities or reduce mission durations.

Pathfinder



Strategic Perspective

Chapter 7 *Strategic Perspective*

Pathfinder will allow NASA's Office of Aeronautics and Space Technology to develop critical capabilities to enable future missions of solar system Exploration. This goal will be pursued vigorously over several years, guided by stable technology objectives against which real progress can be made and measured. Pathfinder must nevertheless be responsive to the changing needs of the Agency. Without constraining the program to the technology needs of any single system or mission concept, year to year planning for Pathfinder must occur in a strongly-grounded strategic context.

That strategic perspective is provided by a projection of potential solar system exploration missions. From that projection, technologies are identified that will either enable or significantly enhance those missions. As noted in Chapter 6, the missions include piloted missions (such as a mission to Mars, or the beginning of operations on the surface of the Moon), and robotic missions (such as robotic precursors to human missions or ambitious sample return and outer planet missions). The technologies needed for those missions fall broadly into the four thrusts of Pathfinder, and are crystallized within those thrusts into elements that will meet critical functional mission needs.

This approach, applied to annual program planning, will allow Pathfinder to balance

the need for stability in research programs against the detailed technology needs of specific, but sometimes rapidly changing, mission designs. Moreover, as Pathfinder technologies reach maturity and are adopted by early mission users, this strategic perspective on the technology needs of solar system exploration will permit the elegant and timely evolution of detailed element program goals and objectives.

Pathfinder technologies will be developed for future civil space missions. At the same time, however, those technologies will undoubtedly find broader applications outside of NASA, both on Earth and in space.

For example, in the Surface Exploration program area, Planetary Rover technolo-



gies, such as autonomy and mobility, will have numerous terrestrial applications either for national defense, or for high-risk civil uses such as toxic waste disposal or fire fighting. Sample Acquisition, Analysis, and Preservation technologies, such as tools, sensors and expert systems, may find applications in remote resource exploration,

in enhanced conventional mining operations, or in low-cost, small-size laboratory instruments. Also, Autonomous Lander technologies, such as the realtime integration of data from multiple sensors, will benefit aeronautics and aircraft safety through risk-reducing autonomy and sensor systems.

In-Space Operations technologies will also find wide applications in private space ventures and in terrestrial endeavors. For example the Resource Processing Pilot Plant program will develop integrated and highly automated mechanical and chemical processing plant systems. Also, the capability to perform In-Space Assembly and Construction will be of great value to future commercial GEO communications satellites.

Humans in Space research and technology will provide valuable information about the impact on productivity of interrelationships between workers and their environments in a high-technology setting. Similarly, stud-

ies of physical-chemical and bioregenerative life support systems will produce important new information on how ecological systems work, and perhaps why they fail.

Lastly, space transfer technologies such as advanced chemical propulsion and aerobraking, although specialized for space applications, will provide further engineering expertise in materials and structures, the use of aerodynamic and aerothermodynamic modeling, and design for high-speed aircraft and spacecraft.

Across a wide spectrum of disciplines and needs, during the coming decade, Pathfinder can push American technology forward. In the same way that the Apollo program did during the 1960s, Pathfinder represents a strategic investment in research and technology that is critical to the civil space program and to the nation.

Glossary of Acronyms

A&R	Automation & Robotics
AFE	Aeroassist Flight Experiment
AI	Artificial Intelligence
ALARA	As Low As Reasonably Achievable
ALS	Advanced Launch System
A-OTV	Aeroassisted-OTV
ARC	Ames Research Center
ASEB	Aeronautics and Space Engineering Board
BNI	Bold New Initiative
CELSS	Controlled Ecological Life Support System
CNSR	Comet Nucleus Sample Return
COSMIC	Coherent Optical System of Modular Imaging Collectors
CRAF	Comet Rendezvous and Asteroid Flyby
CSTI	Civil Space Technology Initiative
DSN	Deep Space Network
DoD	Department of Defense
DoE	Department of Energy
E	OSSA
EB	OSSA Life Sciences Division
EL	OSSA Planetary Exploration Division
ELV	Expendable Launch Vehicle
Eos	Earth Observing System
ETO	Earth to Orbit
EVA	Extra-Vehicular Activity
FY	Fiscal Year
GCR	Galactic Cosmic Ray
GPBS	Gigabytes per second
GEO	Geostationary Earth Orbit
GES	Ground Engineering System

Glossary

GN&C	Guidance, Navigation, and Control
GSFC	Goddard Space Flight Center
H-A-R	Human-Automation-Robotic (Systems)
HLLV	Heavy Lift Launch Vehicle
Isp	Specific Impulse
ISPP	In-Situ Propellant Production
JANNAF	Joint Army, Navy, NASA, Air Force (Propulsion Committee)
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
K	Kelvin
kg	Kilogram
KSC	Kennedy Space Center
kWe	Kilowatts-Electric
kWt	Kilowatts-Thermal
LANL	Los Alamos National Laboratory
LaRC	Langley Research Center
L/D	Lift to Drag Ratio
LEO	Low Earth Orbit
LeRC	Lewis Research Center
LDR	Large Deployable Reflector
LGO	Lunar Geoscience Observer (Mission)
LH	Liquid Hydrogen
LOX	Liquid Oxygen
LTEF	Laser Technology Experiment Facility
m	Meter
Mbps	Megabits per second
mm	Millimeter
μm	Micrometer
MO	Mars Observer (Mission)
MOA	Memorandum of Agreement
MPD	Magnetoplasmdynamic (Thruster)
MPFP	Materials Processing Factory Platform
MR	Mars Rover (Mission)

MRSR	Mars Rover/Sample Return (Mission)
MSR	Mars Sample Return (Mission)
MSFC	Marshall Space Flight Center
MW	Megawatts
NAC	NASA Advisory Council
NASA	National Aeronautics and Space Administration
NAS	National Academy of Sciences
NASP	National Aerospace Plane
NCOS	National Commission On Space
NEP	Nuclear Electric Propulsion
NRC	National Research Council
OAST	Office of Aeronautics and Space Technology
OEXP	Office of Exploration
OMV	Orbital Manuevering Vehicle
OSF	Office of Space Flight
OSO	Office of Space Operations
OSS	Office of Space Station
OSSA	Office of Space Science and Applications
OTA	Office of Technology Assessment
OTV	Orbital Transfer Vehicle
PhD	Phobos/Deimos
PLSS	Portable Life Support System
PRFE	Planetary Return Flight Experiment
R	OAST
R&T	Research and Technology
RC	OAST Information Sciences and Human Factors Division
RF	OAST Aerodynamics Division
RF	Radio Frequency
RM	OAST Materials and Structures Division
RP	OAST Propulsion, Power, and Energy Division
RS	OAST Space Directorate
RTG	Radioisotope Thermoelectric Generator
RTLTL	Round Trip Light Time

Glossary

RX	OAST Flight Projects Division
S	OSS
SAAP	Sample Acquisition, Analysis, and Preservation
S/C	Spacecraft
SLM	Spatial Light Modulators
SP-100	Space Power-100
SPE	Solar Particle Event
S/S	Space Station
SSEC	Solar System Exploration Committee
SSTAC	Space Systems Technology
STIG	Space Technology Interdependency Group
STS	Space Transportation System
STV	Space Transfer Vehicle
TPS	Thermal Protection System
VGRF	Variable Gravity Research Facility
VLBI	Very Long Baseline Interferometry
WBS	Work Breakdown Structure
Z	OEXP

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